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COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERICAL AIR TRANSPORTATION

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FINAL REPORT

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COST/BENEFIT TRADE-OFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERICAL AIR TRANSPORTATION (RECAT)

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FOREWORD

The purpose of the RECAT study has been to provide guidance on the direction future NASA research should take to conserve fuel in the commercial air transport system. To this end, a number of fuel conserving options were defined, none of which represents the likely future evolution of the system, but each of which includes potential elements of the future system. Therefore the predictions of fuel usage, as well as fuel saved relative to the baseline case, should not be employed to draw conclusions regarding the single best direction for research. Rather, the reasons why certain options did or did not result in large estimated fuel savings should be analyzed and understood in order to determine whether a productive direction for research is implied in each case. In this report an attempt has been made to restrict the analysis of results to those areas where clear interpretations can be made and to stress the underlying reasons behind those results.

This study was performed by UTRC under contract to NASA, Ames Research Center. The NASA Technical Monitor was Mr. Louis J. Williams, of the Research Aircraft Projects Office. Associate contractors in the study were the Douglas Aircraft Company, Lockheed-California Company and United Airlines.

Cost/Benefit Trade-Offs for Reducing the Energy Consumption of Commercial Air Transportation

(RECAT)

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Cost/Benefit Trade-offs for Reducing the Energy Consumption of Commercial Air Transportation

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SUMMARY

A study has been performed to evaluate the opportunities for reducing the energy requirements of the U.S. domestic air passenger transport system through improved operational techniques, modified in-service aircraft, derivatives of current production models, or new aircraft using either current or advanced technology. Each of the fuel-conserving alternatives has been investigated individually to test its potential for fuel conservation relative to a hypothetical baseline case in which current, in-production aircraft types are assumed to operate, without modification and with current operational techniques, into the future out to the year 2000.

Specific fuel-conserving options examined in the study, in addition to the baseline case, are:

- Operational procedures with and without advanced Air Traffic Control (ATC)
- Retrofit to, or modification of, current aircraft types
- Derivatives of current aircraft types
- New near-term aircraft using current technology
- New far-term aircraft (propfan and turbofan) using advanced technology

Characteristics of each of these options, as they affect either the aircraft themselves or the system in which they operate, were developed by associate contractors in the study effort, and the system effects were analyzed by the United Technologies Research Center (UTRC). Aircraft and operational characteristics were developed by Douglas and Lockheed. These data were then reviewed by United Airlines to insure consistency and realism in the economic and operational parameters characterizing each option, and the data were then transmitted to UTRC for systems analysis.

In the UTRC analysis of the air transport system, the fuel-conserving options were not simply introduced into the future system by mandate; rather, elements of each option were accepted into the system only as they could compete in an economic sense, thereby promoting realism as to the air transport system which would evolve from each option. The air system simulation involved the generation of the required fleet to meet the forecasted travel demand in each of four forecast years -- 1980, 1985, 1990, and 2000. The forecasted

demand is itself affected by the quality of service offered in each option as measured by fare, trip time, and service frequency, since one element of the demand forecasting process involves a modal split among all competing transportation modes (air, rail, bus, and automobile).

Complete travel statistics for each option -- passenger flow, fuel consumed, air system costs, environmental (noise and emission) impacts, and details of the aircraft fleet--are computed anually and cumulatively, and are compared with the baseline case and with each other. The fuel conserving potential of each option is thus displayed for purposes of evaluation. In addition, other effects of each option -- demand satisfied, user cost and time, noise and emissions, and required government spending -- are evaluated in a benefit/cost analysis to add insight into conclusions derived from energy considerations alone. Based on the results generated in the system simulation, impacts of each fuel-conservation option on airlines, the aircraft industry, air travelers, airports, and the government are quantified, and regulatory implications associated with the possible impacts are discussed. Finally, broad recommendations as to advisable action relating to the fuel-conservation effort are offered.

CONCLUSIONS

Modeling Validity

1. The 600 city-pair system on which the RECAT simulations were based provides a very good representation of the U.S. domestic air transportation system. In terms of origin-destination demand, the system accounts for 62 percent of the round-trip air passengers and 64 percent of the air passenger-miles; on the basis of enplanements, it comprises 83 percent of the air passenger-trips and 86 percent of the air passenger-miles. Consequently, the simulation of fuel-conservation options in the study is adequately representive of the domestic scheduled air carrier system.

2. When the passenger/fleet assignment model was tested to duplicate the 1973 fleet, very good results were achieved, both with respect to total fleet size and fleet composition by airplane type, thereby indicating the validity of the fleet forecasts with fuel-conservation options.

Baseline Results

1. In the baseline case, wherein only aircraft presently in production are available for assignment throughout the forecast period, a 37.1 percent improvement occurs in air system fuel efficiency (pass-mi/gal) between 1973 and 1980, and minor improvements in later years. However, more than half of this improvement comes from study ground rules concerning increased load factor and seating density. Based on fleet mix alone, i.e., replacement of older models by less fuel-intensive airplanes, particularly wide bodies, a 13.1 percent fuel efficiency gain occurs by 1980. Although further gains occur in later years, increased use of wide bodies on short, high-density routes, where their efficiency is not better than smaller models, depresses the magnitude of these additional savings.

2. The effect of doubling the fuel price in the baseline case leads to a required fare increase which results in a significant reduction in short-term (1980) demand. In terms of percentages, the reduction in demand is slightly greater than the saving in fuel so that fuel efficiency is actually reduced with high-priced fuel. In later years the fuel price effect diminishes because, with projected increasing income, fare becomes a smaller portion of total trip disutility (cost).

3. The primary mechanism by which fuel could be conserved in a short-term fuel-allocation scenario would be by increasing load factor. However, a load factor increase alone could be counter-productive because the operating cost

saving it would be reflected by a fare reduction (assuming fixed return on investment (ROI) at the 12 percent CAB value) which would stimulate demand and thereby tend to increase fuel use. A more realistic fuel-allocation scenario, in which load factor is raised to 70 percent while simultaneously holding fares fixed at the baseline values, results in fuel savings of from 20.1 percent in 1980 to 26.1 percent in 1990 and 23.5 percent in 2000. An alternative fuel-allocation scenario characterized by arbitrarily restricting the increase in fuel used to 50 percent of the baseline increase achieves smaller savings in the short term (6.5 percent in 1980), but greater long-term savings (22.5 percent in 1990 and 32.5 percent in 2000). However, these fuel savings may not be achievable in practice because they entail very high system load factors for which there is no historical precedent. In particular, it is possible that significant demand rejection might occur under such conditions, a factor which was not specifically modeled in the simulations.

4. A significant effect in the fuel-allocation scenarios is increased use of three-engine wide-body aircraft (3EWB) relative to the baseline, and reduced reliance on larger four-engine wide bodies (4EWB). The reason for this difference in fleet composition is the higher fuel efficiency of the 3EWBs as compared with 4EWBs. (The fleet assignment algorithm was instructed to select aircraft on the basis of fuel efficiency rather than ROI in the fuel-allocation scenarios.)

Fuel-Conservation Options

Operational Procedures Options

1. Implementation of changes in operational procedures to conserve fuel, within the present air traffic control (ATC) system, produces a measurable saving in fuel at a negligible investment cost. The measures primarily responsible for this saving are aerodynamic cleanup and improved engine maintenance standards. However, part of this saving comes from speed reductions which increase operating costs and fares, thereby depressing demand. On the basis of fuel efficiency (seat-mi/gal), there is an improvement (relative to the baseline case) of from 2.6 percent in 1980 to 3.3 percent in 2000. These improvements are accompanied by demand reductions (enplaned air pass-mi) of from 5.7 percent in 1980 to 2.8 percent in 2000.

2. If gradual upgrading of the ATC system brings about significant reductions in unproductive time in the enroute and terminal phases of flight, further improvements in fuel use can be effected. Assuming a block time reduction of 5 minutes/flight for each major hub in 1985 and beyond, and incorporating the operational procedures changes as well, fuel efficiency rises to about a 5 percent improvement over the baseline case. In terms of total fuel used, this

gain is largely negated by an equivalent stimulation in demand which is caused by reduced operating costs and fares.

Retrofit/Modification Options

1. Based on the projected retirement of existing aircraft, particularly four-engine narrow bodies (4ENBs), retrofit/modification options result in annual demand-adjusted fuel savings (relative to the baseline) of between 0 and 6 percent in the 1980s. Slightly higher cumulative savings are achieved when JT4- and JT3D-powered 4ENBs are reengined with more efficient refanned JT8Ds than if reliance is placed strictly on aerodynamic modifications.

2. An even more effective option in the 1980s is to restrict the modifications to newer aircraft types only, i.e., no retrofit of out-of-production models which are retired according to the more rapid baseline schedule. This strategy results in about a 1 percent additional savings in annual fuel use in the 1980s. Although retrofit/mod options should be viewed primarily for their near-term impact, the cumulative savings out to the year 2000 are not very different in any of the cases studied.

3. When the basic retro/mod options are considered under the assumption that no retirements of existing models occur in the period from the present time (1975) to 1980, results change significantly. Because a delayed retirement schedule causes the retention of less fuel-efficient aircraft in the fleet for a longer time, annual fuel savings, relative to the nominal retirement schedule, are considerably reduced in the 1980s.

4. In the retro/mod options, the investment in new equipment, including retrofitting existing aircraft, is almost directly related to fuel savings. Delaying retirements by investing in retrofits yields the smallest fuel saving but also the smallest investment, and vice versa. If far-term (2000) results are disregarded, the best retrofit/modification option on a system basis appears to be one in which out-of-production aircraft presently in the fleet are not retrofitted and are retired by the mid-1980s, while existing and new deliveries of in-production aircraft are modified for improved aerodynamic efficiency.

Aircraft Derivative Options

1. Of the eight derivative aircraft provided by the manufacturers, only three were economically attractive enough to compete successfully with baseline in-production models. The remainder were either not assigned to any routes or were assigned in such small numbers that they were best omitted.

2. Of the three derivatives that were assigned in significant numbers -- DC-9-30D1, DC-10-10D, and L-1011L -- the L-1011L was clearly the most attractive airplane. It has a large seating capacity, a low price and good fuel efficiency, making it an excellent replacement for the B-747 over the dense short and intermediate stage lengths to which that airplane had to be assigned in the baseline case for lack of a good alternative.

3. In the basic derivative option, significant savings in demand-adjusted annual fuel use (17.1 percent) and cumulative fuel over the baseline case (9.7 percent) were achieved by the year 2000. However, these savings were due almost exclusively to the favorable impact of the L-1011L. When the L-1011L was omitted, annual demand-adjusted savings diminished to only 1.5 percent and cumulative savings to 1.3 percent. Therefore, the availability of an airplane with the fuel efficiency and cost parameters of the L-1011L would have a very favorable effect on fuel conservation.

New Near-Term Aircraft Option

1. The new near-term aircraft option is similar to the derivative case in that it combines relatively early availability with good improvement in fuel efficiency over baseline in-production airplanes. The favorable economic characteristics of these airplanes resulted in rapid introduction into the fleet, which is a vital prerequisite to achieving an impact on fuel conservation.

2. By the year 2000, new near-term aircraft comprised more than 60 percent of the fleet, thereby resulting in annual demand-adjusted fuel savings of 20.5 percent over the baseline case, and cumulative savings of 11.6 percent. This effect was achieved primarily through displacement of the B-747 and, to a lesser extent, the DC-10/L-1011 and B-727-200.

New Far-Term Aircraft Options

1. The far-term options featuring the 200-passenger propfan with 1985 technology (N85-200P) did not produce large fuel savings, despite the very good fuel efficiency of the airplane. Basically, the disappointing results occur because only one airplane was introduced, its design range restricted its assignment to routes under 1500 miles, and its capacity was not big enough to displace existing wide bodies on the most dense routes. Even when the N85-200P was given the benefit of an early introduction (prior to 1985), its impact on fuel conservation was compromised by the above limitations.

2. Very large fuel savings were achieved by the far-term aircraft options which consisted of one large airplane (the N85-500) and one smaller airplane (either the N85-200 or the N85-200P). Cumulative demand-adjusted savings of

11.9 percent, relative to the baseline case, were achieved by the year 2000 even though the airplanes did not enter service until after 1985. By the end of the period, far-term aircraft comprised almost half of the fleet.

Impacts Analysis

1. Airlines: Improvements in ATC are beneficial to the airlines because they facilitate lower-cost operations without direct airline investment. The basic derivative option is also favorable from an airline viewpoint, especially in the long term, because of the relatively small investment required.

2. Manufacturers: Manufacturer impacts are more favorable in the short term than in long term. The operational procedures option with ATC improvements is attractive to manufacturers for the same reason it is attractive to airlines. Retrofit/mod options are basically unattractive to manufacturers because they delay airline investment in new equipment, and because some of the retrofits will be done by the carriers themselves. Overall, the new near-term aircraft option offers the most business to manufacturers, although all the derivative and new-aircraft options give some improvements compared with the baseline case.

3. Airports: If airport activity is the most important measure, the best airport impacts are produced by the new-and derivative-aircraft options in which large, low-noise airplanes predominate. Retrofit options are poor because they retain older, noisier aircraft longer than the baseline.

4. Government: Derivative-and new-aircraft options save the most fuel and give the best emissions reductions. Retrofit options are undesirable because they save less fuel than the high-technology options and because they increase emissions over the baseline. Of the derivative- and new-aircraft options, those options which require new technology involve considerably more R&D expense than those which do not, thereby favoring either the derivative or the new near-term aircraft options. However, the greater fuel saving of the far-term aircraft option helps to offset this cost.

RECOMMENDATIONS

The UTRC portion of the RECAT Study did not provide a strong basis for the formulation of technology recommendations. Technology aspects were treated by the other contractors in the specification of aircraft designs, and these designs were employed in the fleet forecasts. Nevertheless, some of the primary results of the UTRC study do have implications for future research and technology effort.

Recommendation No. 1: Design of a large-capacity airplane aimed at good economic and fuel consumption characteristics, specifically for short and intermediate stage lengths

Much of the fuel savings estimated in the forecasts, including the baseline option, derived from the replacement of existing narrow-body airplanes by wide bodies. Although this replacement occurred over a broad spectrum of stage lengths where very high service frequencies would have been required with narrow-body aircraft, fuel efficiency gains were not universal because, at short stage lengths, the fuel efficiency data for currently available wide bodies was poorer than for the narrow bodies they replaced. Therefore, fuel efficiency gains tended to level off with time in the baseline option as present wide bodies were used at progressively shorter average stage lengths. A consequence of this leveling off in the baseline was that those technology options which offered a more fuel-efficient replacement in the high-volume markets achieved significant gains over baseline fuel usage.

Despite the fuel savings that were estimated in the derivative-and new-aircraft options, the large-capacity aircraft which generated the savings were not necessarily conceived with good short-stage economics and fuel efficiency in mind. It would appear, therefore, that even greater fuel savings would be achieved if an advanced wide-body airplane were designed specifically for the short-to-intermediate-range market. Such a design would have to stress features normally found only in smaller aircraft, such as ease of maneuvering on the ground, good airport compatibility, and general attractiveness for short-haul operations. Since the RECAT designs may not include such features, their assignments in this study may be overstated. However, the historical trend of steadily increasing aircraft size is likely to accelerate in the future as a means of forestalling airside congestion at busy airports. Therefore, the decision to graduate to the largest aircraft capacity available may be forced by future growth. The results of the baseline case show that efforts to conserve fuel would be severely compromised if reliance is placed on presently available (long-range) wide-bodies.

Recommendation No. 2: More precise determination of the cost incurred and fuel saved by improvements in operational procedures

A second research and technology option has been identified with respect to improvements in operational procedures. Of all the fuel-conservation alternatives, procedural improvements offer the most immediate fuel-conservation benefits. Even though the fuel savings which are achievable by procedural changes may only amount to a few percent, the fact that early implementation is possible, plus the likely compatibility of procedural improvements with technology advances, makes this alternative worthy of further interest.

In the RECAT study, the procedural improvements were defined in rather general terms. Rough estimates were made by the manufacturers of percentage fuel reductions for various airplanes in each of several categories such as speed reduction, climbing cruise, etc. These estimates were then reviewed by UAL, although only minor changes were made, and it appeared that uncertainty existed with respect to the practicality of the suggested changes, particularly with regard to the possible cost of their implementation; however, cost estimates were not made.

It is recommended that further study be made of operational procedures in order to ascertain the real fuel savings that can be achieved and to identify the costs involved so that the likely implementation of the procedures can be addressed. The impact of fuel price and availability must be an important aspect of such studies. Furthermore, the gathering of basic technical and economic data to permit a better evaluation of procedural changes may be in order. An example is the economic trade-off between the increased cost of more frequent maintenance of engine and airframe systems and the decreased cost of fuel due to improved efficiency. Credible estimates of the cost of such measures and the fuel savings they facilitate may prompt carriers to adopt them more readily.

Recommendation No. 3: Design propfan-and turbofan-powered airplanes with equivalent technology assumptions in order that a fair comparison can be made between these propulsion alternatives.

The true fuel conservation potential of the propfan was not determined in the RECAT study because only one propfan-powered design was incorporated in the far-term aircraft options, and because the size and airframe technology assumptions of this design were not entirely compatible with the far-term,

turbofan-powered designs. Nevertheless, on the basis of fuel efficiency, the propfan airplane had an advantage over an equal-capacity turbofan airplane. Therefore, there is good reason to believe that fuel would be saved by switching from turbofan to propfan power if the comparison were made equitably. It is recommended that several propfan and turbofan aircraft be designed with seating capacities from 200 to at least 400, and with completely compatible assumptions as regards airframe and engine technology. These airplanes would then be compared as alternative options to future fuel conservation. The more attractive propulsor would then be utilized in the scenario comparisons recommended below.

Recommendation No. 4: Further study of a realistic scenario (or scenarios) which combine discrete fuel-conserving options for maximum benefit

A final recommendation relates to the question of how to better estimate the actual fuel savings advanced technology will bring. The nature of the RECAT options was quite selective; each one provides an indication of the conservation potential of one particular development and its implementation, but no single option, including the baseline, describes a likely future scenario. Therefore, strategies for future fuel savings cannot be well-formulated on the basis of present RECAT results. Rather, the best RECAT options should be considered in various combinations to determine which options complement each other and which conflict. The potential savings available from an evolutionary strategy in which procedural and technology improvements are viewed together, rather than as alternatives, would provide a firmer basis for research and technology policy formulation. The model assembled in the RECAT study, and the aircraft data which were generated, are well adpated to further analyses of this type.

INTRODUCTION

Although the portion of transportation petroleum fuels consumed by commercial aircraft is only about 7 percent, it is generally recognized that airplanes compare unfavorably with other transportation vehicles in terms of energy intensity, though the deficiency is often overstated. This unfavorable position is related closely to the high installed power-to-weight ratio of the airplane, a consequence of its high speed, but considerations such as passenger and freight loadings, seating density, stage length and selected cruise speed are contributing factors. Historically, airplanes, like other transportation vehicles, have not been designed with fuel consumption as the primary consideration because the ready availability and relatively low cost of petroleum fuels did not warrant major emphasis on this one factor in the operating cost equation. This situation changed abruptly in recent years, as improved fuel economy has emerged as a high-priority research area throughout the transportation sector. Because of their high energy intensity, commercial aircraft are receiving a larger share of this attention than would appear appropriate considering the small fraction of the nation's fuel they consume.

There are numerous ways by which aircraft fuel consumption can be reduced. These measures range from procedural improvements in the system to new designs incorporating advanced-technology components. Each alternative for saving fuel carries with it a cost and an implementation period which complicates the comparative evaluation process. Only a thorough analysis can sort out the costs and benefits of these alternatives and show them in context. The objective of this study has been to consider a wide range of fuel-conserving options and to determine the cost/benefit trade-offs attendant to each.

Study Organization

The structure of the RECAT Study was unusual in that NASA selected four contractors to carry out separate but interdependent studies. The contractors included two airplane manufacturers: Lockheed-California Company (LCC) and Douglas Aircraft Company (DAC); one operator: United Airlines (UAL); and one consultant: United Technologies Research Center (UTRC). Although these participants were separately contracted to perform their individual tasks pursuant to the accomplishment of the study objective, the nature of the tasks was such as to require close coordination throughout the study, including mutual agreement on ground rules and methodology as well as sharing of data. The division of tasks among the RECAT contractors can be generally summarized as follows:

Contractor	Primary Responsibility
Manufacturers	Aircraft Designs, Modifications, Derivatives
Operator	Design Review; Documentation of Current Airplanes
Consultant	Demand and Fleet Forecasting; Benefit/Cost Analysis of Fuel-Conserving Options

Although the demand and fleet forecasting task was the primary one in the UTRC study, several other tasks were also carried out, including:

1. development of a plan to coordinate the study;
2. an assessment of the foreign market for used U.S. commercial aircraft;
3. an estimate of the fuel used by all-cargo and international aircraft;
4. consideration of the regulatory effects of fuel-conservation strategies;
5. definition of new, far-term, fuel-conserving aircraft based on the Boeing Terminal Area Compatibility Study;
6. implementation of a fleet assignment model in combination with demand and modal-split models;
7. determination of the impacts of fuel-conservation measures on operators, manufacturers, government, airports, and travelers;
8. a benefit/cost analysis comparing the fuel-conserving options; and
9. recommendation of research and technology areas for fuel conservation based on the RECAT results.

The first two of these tasks were documented in the Interim Study Report, Ref. 1, and are not included in this report. The results of the third task are used in Appendix A to estimate fuel used by U.S. certificated carriers, and the derivation of far-term fuel-conserving aircraft is provided in Appendix B. All remaining tasks are documented fully in the main body of this report.

Fuel-Conservation Options

Qualitatively, four types of fuel-conservation alternatives were considered in this study: improved operating procedures; modification of existing aircraft models; derivative models of existing aircraft; and newly designed aircraft. The specific options for which results are presented in this report include several examples from each of these categories in addition to a baseline case in which the nominal evolution of the system was forecast in the absence of further fuel-conservation measures. Moreover, in view of the uncertainty of fuel price and availability in the future, several cases were studied with baseline assumptions except for higher fuel price and/or restricted fuel availability. In all cases, forecasts were made for the years 1980, 1985, 1990, and 2000, and comparisons were made with the base year, 1973. A summary of the fuel-conserving options considered in the RECAT Study appears in Table I. The specific features of each option are described in greater detail in a later section of this report, but can be summarized as follows.

In the Baseline Option (I) only those aircraft listed in the "In-Production" column were assumed to be available as replacements for retired airplanes and to accommodate demand growth in the forecast years. As conceived, the Baseline Option represents an extension of present aircraft usage into the future. No fuel-conservation measures are enforced, beyond those already being practiced by airlines in 1973, and no new or derivative aircraft are introduced in the forecast period which extends to the year 2000. Although this definition of the Baseline Option is severe in that these assumptions are quite conservative and probably not realistic, it does represent a tractable datum from which to measure the effects of system improvements on fuel consumption. Furthermore, the range of seating capacities covered by the baseline aircraft is broad enough (92 to 386 seats) to keep flight frequencies within manageable bounds. These same airplanes were retained as competitors to new and derivative aircraft in Options IV to VI; i.e., the fleet forecasting model was presented with a mix of available aircraft, for assignment to each route, which always included at least the baseline in-production airplanes.

The Operational Procedures Option (II) was included to obtain an estimate of the fuel savings achievable by improvements in airline operations. These improvements are divided into two catagories: Option IIa, which incorporates airline operations and maintenance measures compatible with the present ATC system through relatively minor adaptations, and Option IIb, which combines these measures with an improved ATC environment assumed to be in existence by the mid-1980's.

TABLE I

RECAT FUEL CONSERVATION OPTIONS

Option	Description	In-Production Aircraft	Year of Introduction	First Forecast Year
I Baseline	Extension of present aircraft usage. No fuel conservation measures beyond 1973 practice. No new or derivative aircraft.	B-737-200; DC-9-30; B-727-200; DC-10/ L-1011; B-747-200	1973	1980
IIa Operational Procedures	Procedural improvements: Speed reduction to Long Range Cruise Speed; 2000 ft step climb; Load to aft c.g.; Aerodynamic clean-up; Reduction in Operating Empty Weight; Improved engine standard; No ATC improvements	Same as Baseline	1977	1980
IIb Operational Proc. with ATC	Procedural improvements in IIa plus improved ATC	Same as Baseline	1977/1985	1980/1985
IIIa Aero Retrofit	Selected modifications to in-service aircraft: Aerodynamic cleanup; Winglets; Fairings; No engine retrofit	Same as Baseline	1978 to 1982	1980
IIIb Aero Retrofit Reengine	Selected modifications including JT8D Re-engine of JT3D-powered airplanes	Same as Baseline	1978/1979 to 1982	1980
IV Derivatives	Selected derivatives of DC-9, DC-10, L-1011, B-727	Same as Baseline plus Derivatives	1979	1985
V New Near-Term Aircraft	New designs incorporating current technology features	Same as Baseline plus N80s	1980+	1985
VI New Far-Term Aircraft	New designs incorporating advanced technology features	Same as Baseline plus N85s	1985+	1990

Options featuring retrofits or modifications of existing airplanes (Option III) are also divided into two categories: Option IIIa includes aerodynamic modifications specifically tailored to each of the baseline in-production aircraft, and Option IIIb includes these aerodynamic changes plus replacement of JT4 and JT3D engines with refan JT8D engines on first-generation turbojet and turbofan models. In each case, the lifetimes of the retrofitted airplanes are extended to reflect the additional investments incurred by these modifications. Furthermore, new additions to the fleet also include the changes, so that the entire fleet incorporates the retro/mod features by the 1985 forecast year.

Derivatives of the DC-9, B-727, L-1011, and DC-10 airplanes were designed by the manufacturers* for Option IV. These derivatives compete with each other and with their own baseline models for assignments to the 600 city-pair routes in the demand and fleet assignment process. Although introduced in 1980, these aircraft are not assumed to be in airline service in large numbers until 1985.

The new, fuel-conserving, aircraft designs based on current technology (Option V), and advanced technology (Option VI), are introduced in the early and late 1980's, respectively. The near-term designs include the aerodynamic, structural, and propulsion system improvements, over the baseline aircraft, that are available for a design begun in 1976 (e.g., supercritical wings, composites in secondary structure, and JTIOD/CFM56 engine technology). In addition to this technology, further advances are assumed for far-term aircraft, including the use of composites in the primary structure, active controls, and turboprop engines of advanced design.

Report Structure

The intent of this report is to present the results of UTRC's portion of the RECAT study and to document the analytical models by which the results were generated. Since the reader's primary interest is likely to be in the results rather than the methodology, the main body of the report is devoted largely to an exposition of results. However, since the credibility of the results is very much a function of the analytical approach, a section of the main text has been devoted to a description of the Demand and Fleet Model Development phase of the study. Through the unique features of this model it has been possible to represent a large fraction of the domestic air transport system, and to simulate the effects of offering a variety of equipment

* Data for the B-727-300 came from UAL.

types on the characteristics of the system. Therefore, an understanding of the structure of the model is deemed essential to an appreciation of the validity of the results.

In order to improve readability of the main text, documentation of other analyses utilized in the study has been relegated to the Appendices.

MODEL DEVELOPMENT

The major methodological task in the RECAT study was the development of a computerized procedure by which to simulate the passenger and fleet assignment process in the domestic air transport system. The objective of this task was to construct a model which is sensitive to changes in certain study parameters which were expected to vary from option to option. These parameters include fare, particularly as affected by the cost of fuel; service frequency; trip time; and load factor. Only by determining the way the aircraft would be utilized in service can the fuel used in each scenario be estimated.

RECAT Model Structure

A basic element of the model was in hand at the outset of the study. The passenger demand and modal-split models which are used to forecast origin-destination (O-D) air demand in a multi-mode travel environment were previously developed as part of UTRC's Corporate-sponsored program. As shown on the left-hand side of Fig. 1, these programs accept inputs descriptive of future population and income growth, as well as characteristics of the candidate inter-city travel modes (air, auto, rail and bus). These characteristics affect a passenger's choice of mode as expressed by the disutility* of travel.

The second modeling procedure, indicated in the center of Fig. 1, is the passenger and fleet assignment model. The purpose of this program is to convert the forecasted O-D demand to an estimate of the required aircraft on each route in the air transport network. Its development was the primary methodological accomplishment of the study, and most of this section is devoted to a description of its structure.

Before describing the fleet assignment model, however, it is important to understand how the model fits into the overall procedure assembled for the forecast. A general picture of this procedure also appears in Fig. 1, showing not only the models but also the major input and output quantities in each, and the interrelationships which tie the programs together. As shown by the arrows in the figure, a set of feedback loops is present, necessitating an iterative solution to stabilize on appropriate values of the important parameters.

* Disutility is defined as either the total cost of travel (out-of-pocket cost + travel time·value of time) or the total time of a trip (travel time + out-of-pocket cost/value of time).

RECAT SYSTEM MODEL

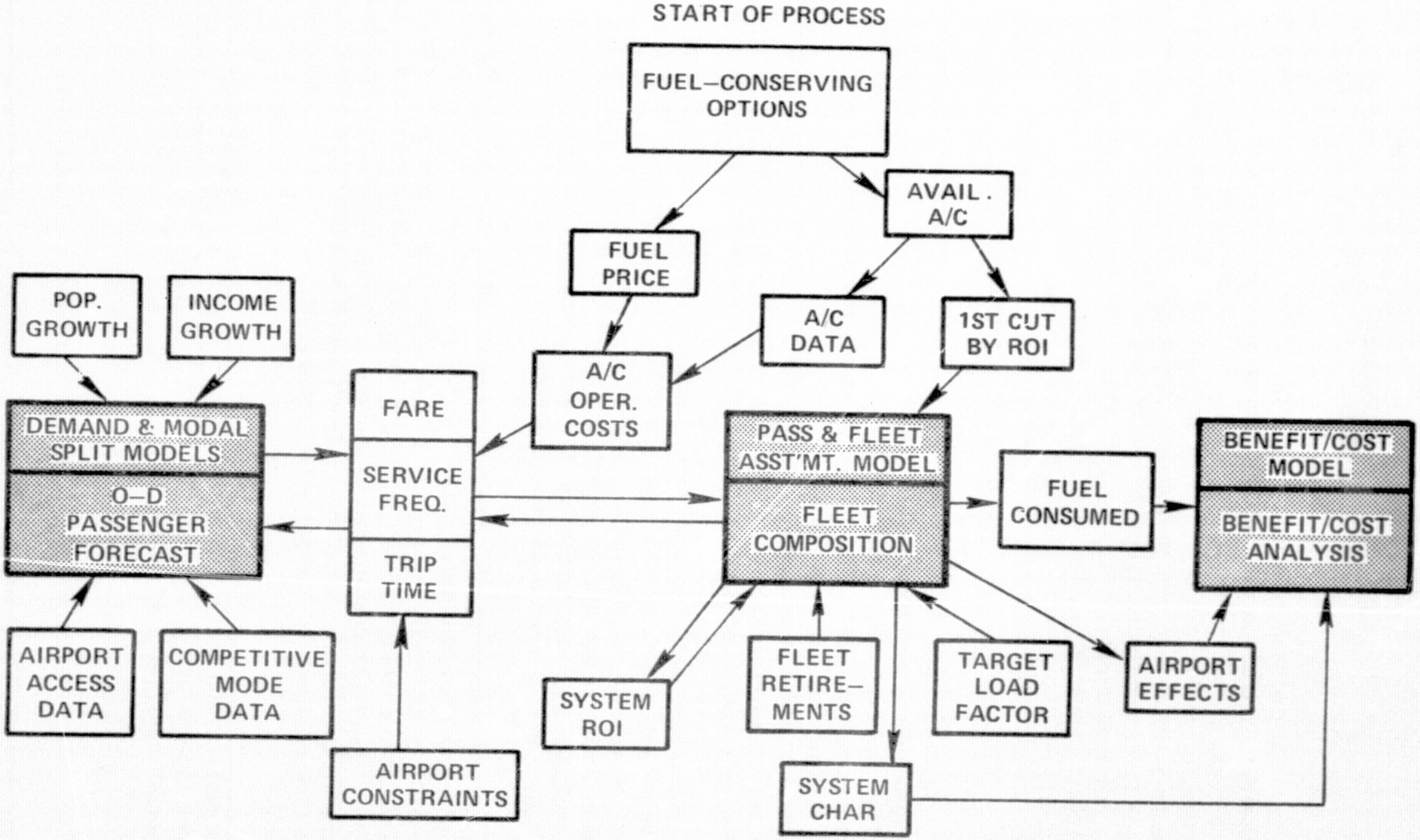

FIG. 1

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Each fuel-conserving option (uppermost box in Fig. 1) is described by a set of aircraft which may include existing types, modifications and/or derivatives of these types, and new aircraft. In addition, a fuel price or a fuel allocation scheme may be specified as part of the scenario. Data descriptive of the aircraft are used as inputs to the calculation of operating cost, and also to make a preliminary aircraft selection (for each route) on the basis of return on investment.* In addition to achieving the best economic performance among those aircraft available in the fleet, a mix of aircraft is selected so as to include a range of passenger capacities.

The operating costs of the airplanes affect the fare level, which is chosen to provide an acceptable ROI (12 percent) for the total system. Similarly, the trip time and service frequencies appropriate to each route, based on the aircraft assigned in each case, provide the necessary inputs for a refinement on the initial estimate of the O-D passenger demand. When this revised demand is used in the passenger and fleet assignment model, a new fleet is composed, and then the process is repeated until convergence is achieved; i.e., demand, fare, and system ROI are in equilibrium.

Results for a particular fuel-conserving option provide a "snapshot" of the total system from which values of important system parameters can be selected. Certainly, total fuel consumed is one of these but, in addition, such quantities as total investment in new aircraft, user costs (fare), operations required at busy hubs, etc. are of interest. Knowledge of the system's characteristics provide necessary inputs to the last of the three modeling procedures indicated in Fig. 1, a Benefit/Cost Model. Using this model, which was developed at UTRC prior to the RECAT study, a benefit/cost analysis is performed in order that the implications of each option can be viewed in terms of its impact on the system, and to put fuel consumption into perspective with other system costs.

Adaptation of Demand and Modal-Split Models

The modal-split model, derived using 1972 National Travel Survey data, is used to compute the share of the travel between two cities captured by each

* The aircraft ROI data used in this first economic screening were provided by United Airlines. Each airplane was evaluated as it would be expected to function in UAL's system, and required load factors for a 15 percent ROI were generated for each stage length. The fleet assignment model then used the load factor ordering of the candidate aircraft as the initial criterion in the assignment process.

of the competing modes. This is done on the basis of the "disutility" associated with each mode; separate computations are made for business and pleasure travelers. A more complete description of the demand and modal-split models appears in Appendix C.

Air shares computed by the modal-split model were combined with air travel data from the CAB Origin-Destination Survey to estimate total travel (via all modes) for 84 city-pairs for the years 1958, 1966, and 1972. These estimates, along with mean disutilities also computed by the modal-split model, were used to develop and validate the demand model. This model computes the demand for transportation between two cities as a function of population, per-capita income, ease of travel as measured by the mean disutility, and the diversionary effects of other cities. The 1958-1972 period spans the conversion from piston to jet aircraft, during which significant changes occurred in block times, fares, and service frequencies; substantial growth in population and income also occurred. The model has thus been validated over a range of input values comparable to the range expected in the 1973-2000 forecast period.

With both models sensitive to the characteristics of air service, changes in those characteristics will affect both the total demand and the air share of the total demand. The total-demand effect is more important on long routes where air would be expected to dominate the other modes under almost any circumstances and the air share is relatively insensitive to service characteristics, while the air-share effect is more important on short routes where auto is the dominant mode, thereby making the total demand relatively insensitive to air service characteristics.

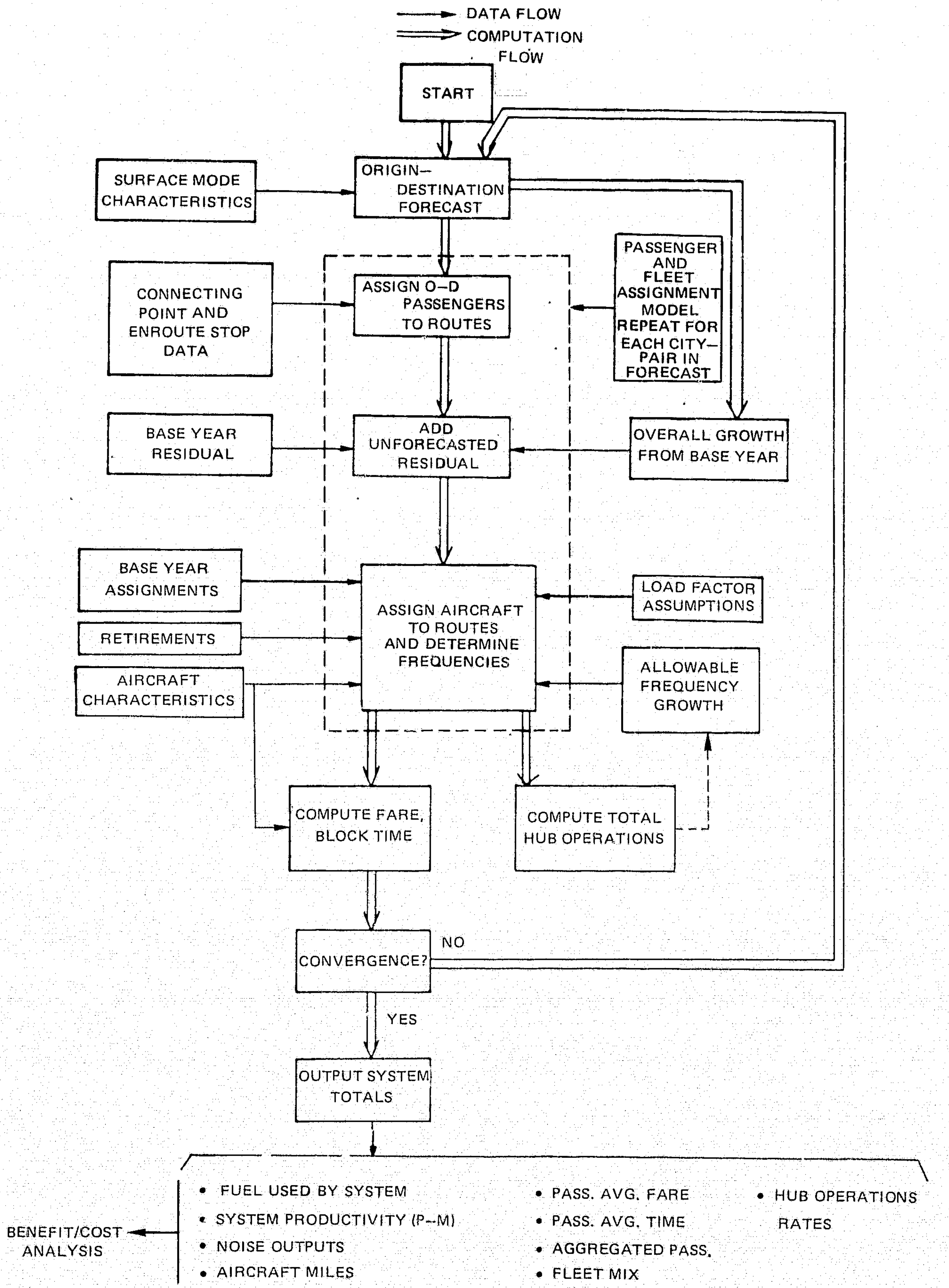
Passenger and Fleet Assignment Model

As stated earlier, the demand and modal-split models and the fleet assignment model are the two principal modules of an iterative procedure to determine the system's operating conditions for each fuel-conserving option to be studied.

The basic program structure is represented by the simplified block diagram of Fig. 2. The first step is computation of the air demand for a 600 city-pair sample using the demand and modal-split models applied to each city-pair. This is the O-D demand reflecting the ultimate endpoints of the traveler's journey, regardless of the routing used. The O-D demand is then assigned to specific routes (city-pairs with nonstop service) using routing data for each city-pair available from Table 12 of the CAB Origin-Destination Survey. Since travelers shown by the CAB as traveling direct

FIG. 2

DEMAND AND FLEET FORECASTING PROGRAM



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may make intermediate stops (without changing planes), enroute stop information from the Official Airline Guide (OAG) is also required. Route assignments may also be influenced by congestion constraints at some hubs, which necessitate use of larger aircraft, and by new nonstop service for growing city-pairs having little or no nonstop service in the base year.

The total passenger flow on each route is found by adding an unforecasted residual to the forecasted O-D flow. This increment represents passengers connecting from the many smaller city-pairs not included in the 600-city-pair forecast. The size of the residual for forecast years is found by taking the base-year value and multiplying by a growth factor.

The next step involves the assignment of aircraft to each route. Base-year aircraft assignments (less retirements) are initially assumed for the forecast years, and new aircraft are added to each route to compensate for retirements* and demand growth. Only one new aircraft type is assigned to each route, with the selection depending upon several factors, including: (1) aircraft return-on-investment characteristics provided by UAL for each of the aircraft types in the study; (2) the size of the aircraft relative to the demand to be satisfied; (3) the target load factor; and (4) the allowable frequency growth in view of possible congestion. The new fleet mix is then used to compute new fares (for a 12 percent system ROI) and block times which, along with the new frequencies, influence the demand and modal-split computations, thereby requiring feed-back to the beginning of the process. This entire procedure continues iteratively until convergence is achieved, typically in three to five cycles. System summaries such as fleet sizes, total fuel consumption, etc. are then output for subsequent use in the benefit/cost analysis.

<u>Data Sources</u>

A considerable volume of data was utilized in order to accurately account for the assignment of the O-D passenger demand by route and to describe the structure of the system as regards utilization of aircraft in the base year (1973). The primary sources were Tables 12 and 13 of the CAB Origin-Destination Survey, the CAB Service Segment Data, and the <u>Official Airline Guide</u> for August 1973. The nature of these sources and the way they have been used in the passenger and fleet assignment modeling process are described in the following paragraphs.

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* The retirement algorithm used to remove old aircraft from the fleet is described toward the end of this section.

CAB O-D Survey

The O-D survey consists of data for each of approximately 45,000 city-pairs. It is constructed from a 10 percent sample of all tickets and describes the routes followed by passengers traveling among these city-pairs. The data are subject to several limitations, primarily in that stopover times at enroute (connecting) points are not indicated, and there is no way of determining if the itineraries noted on the ticket involved enroute stops at which the passenger did not depart the flight. The O-D survey data also include a large volume of extraneous information (for the purposes of this study) concerning the airlines used on each flight segment. Moreover, the great multiplicity of routings used to connect each city-pair complicates the problem of modeling these routings in a straightforward way. In CAB Table 12, an "itinerary" consists of both the city routings and the airlines used on each segment, and the same routing appears several times in a particular city-pair listing. For example, the routing A-C-B (city A to city B with a connection at C) appears as A-a_1-C-a_2-B, A-a_1-C-a_3-B, etc., where a_1, a_2, and a_3 are the airlines used. Furthermore, if one city has multiple airports, either the particular airport or the general designator used on many tickets can appear (i.e., JFK-a_1-C-a_2-B, NYC-a_1-C-a_2-B, etc.). Thus, arriving at an accurate total for a particular routing A-C-B requires the aggregation of many individual data elements scattered throughout a lengthy city-pair listing. (The Table 12 listing for New York-to-San Francisco, for example, is about 135 pages long.) Fortunately, in most cases a few data elements accounted for most of the itineraries and a lower cut-off of 2 percent of the total could be used when tabulating data elements for aggregation.* However, it was necessary to redo a number of long-distance city-pairs using a smaller cut-off value in order to include a reasonable percentage of the total. Eventually, 91 percent of the origin-destination demand was accounted for, with 88 percent traveling direct (i.e., no connections) and 3 percent making connections. (Note that this high percentage of direct trips refers to the 600 city-pair sample which contains many high-density routes.) Of the remaining 9 percent, most were scattered among a great many itineraries which individually accounted for insignificant fractions of the city-pair total, while some should have been aggregated into significant itineraries but were missed because of the cut-off level.

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* Since the limitations of this study did not justify use of computerized data reduction, Tables 12 and 13 of the survey were obtained in microfilm form, and the required data were recorded manually. Although this procedure necessitated some simplifying assumptions to reduce the number of routings to a manageable number, the results describe the system quite well.

Official Airline Guide

Data from the August 1973 Official Airline Guide were processed by computer from a data tape, thus facilitating a complete description of required information for each city-pair. In particular, the average number of nonstop flights per day by each aircraft type, and the associated block times, were computed for each city-pair. Of the 600 city-pairs in the sample, 351 had a low level of nonstop service (defined as five or less flights/day in each direction), including 117 with no nonstop service. For these 351 city-pairs, the number of one-stop flights per day was also tabulated, along with the intermediate-stop city associated with each flight. In addition, the number of connecting flights was determined for each of about 200 city-pairs having low levels of both nonstop and one-stop service. Because of computer limitations, this latter tabulation was done manually. The one-stop data were used to augment the CAB data in assigning passengers to other routes, since the CAB data fail to distinguish between nonstop and other direct (i.e., no connections but one or more intermediate stops) itineraries. This phase of the assignment is predicated on the relative attractiveness of the nonstop vs. one-stop service, based on block time and the schedule inconvenience factor used in the disutility computation.

CAB Service Segment Data

An important source of data for the purposes of this study was the CAB Service Segment Data listing, which tabulates from carrier reports the total number of passengers actually carried on nonstop flights serving a particular route, as well as the departures performed and the load factors. Since these data describe the actual aircraft loadings on each route over which they were used, they were an important supplement to the O-D Survey data in formulating the passenger assignment model. The departure data were used to adjust the August frequencies obtained from the OAG to accurately reflect annual average daily frequencies. Although this correction resulted in frequency adjustments of as much as 60 percent for a few individual city-pairs on which traffic is seasonal, most frequencies were changed by only 10 percent or less, and the total number of operations for each type of aircraft showed negligible change.

A comparison of the fleets required to serve the 600 city-pairs, and the total fleets of the domestic trunk, local service carriers, and appropriate intrastate carriers used in scheduled service, is given in Table II. The required fleets were calculated by converting the average daily frequencies to fleet requirements using city-pair block times and a utilization curve (Fig. 3) derived from 1973 CAB data (Ref. 7). The representation

TABLE II

COMPARISON OF FLEET SIZES AND AVERAGE STAGE LENGTHS

	Total Domestic Fleet[4]		600 City-Pair Fleet	Coverage		Avg. Airplane Stage Length (Statute Miles)	
						Total Dom.	600 City-Pairs
B-747	58	(60)[3]	65	112%	(108%)[3]	1858	1714
DC-10	69	(76)[3]	80	116%	(105%)[3]	980	1034
L-1011	18	(22)[3]	20	111%	(91%)[3]	1199	1347
B-707	143		137	96%		986	1070
DC-8-61/63	43		39	91%		923	934
B-727-200	282		247	88%		484	550
B-727-100	345		286	83%		544	643
B-737-200	145		87	60%		299	360
DC-9-30	230		172	75%		306	403
DC-9-10	84		46	55%		274	373
Turboprop[1]	177		123	7%		119	159
Others[2]	246		180	73%		632	714
Total	1840	(1853)[3]	1372	75%	(74%)[3]	442	639

[1] CV-580/600, F-27, FH-227

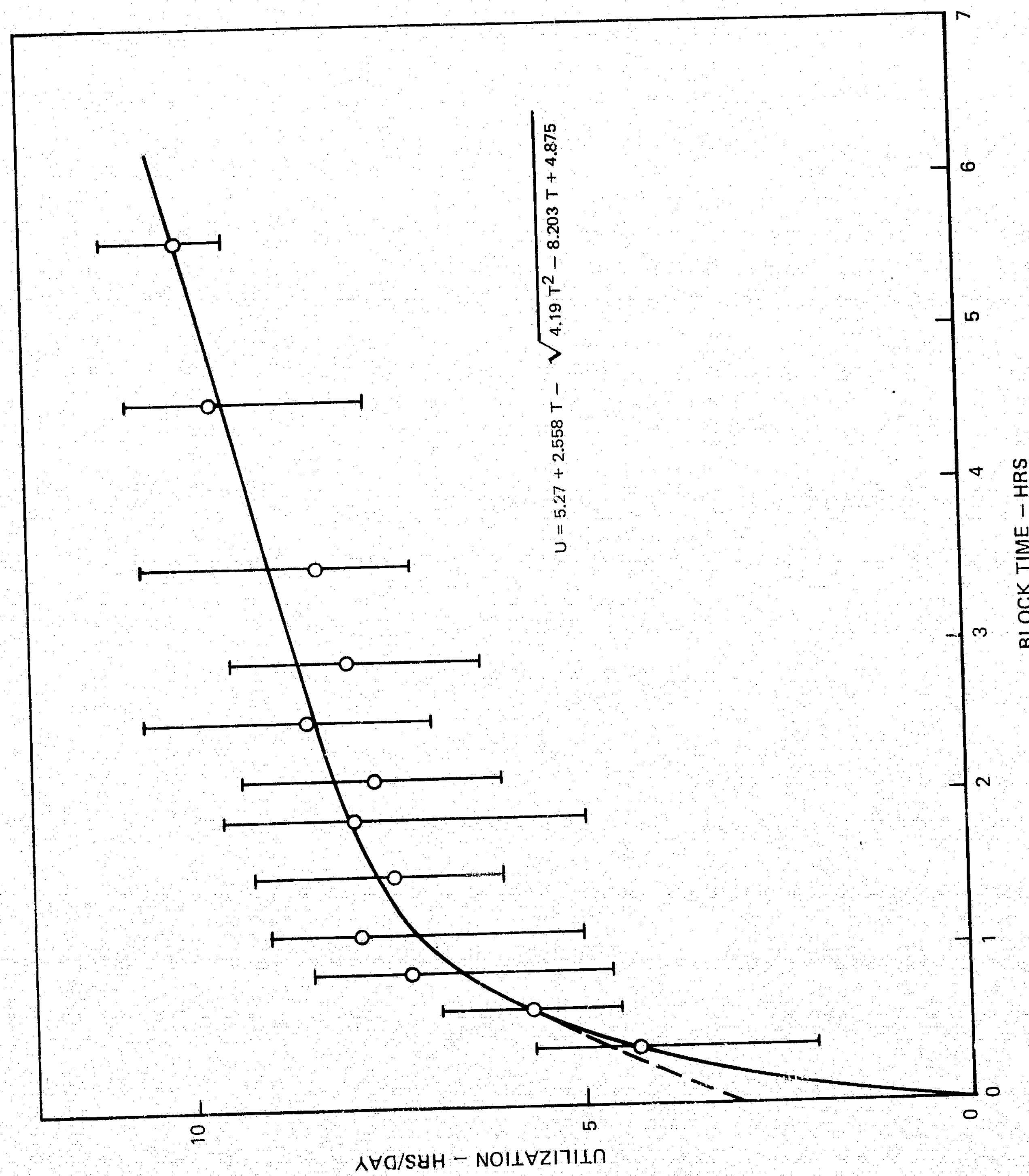
[2] B-720B, DC-8-20/30/50/62, CV-880, BAC-111

[3] 3rd Quarter Fleet

[4] Domestic Trunk, Local Service, and Intrastate Carriers in Scheduled Service

FIG. 3

AIRCRAFT UTILIZATION



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of the total fleet is 75 percent; all aircraft types are well represented except turboprops, which are used primarily on very short, low-density routes, not included in the data base. The wide-body types appear to be overrepresented; this can be partially explained by comparison with the third-quarter (August) fleet data rather than the annual average. Other potential sources for this discrepancy are higher than-average August utilizations, and, possibly, inaccurate reporting by the airlines or the CAB, particularly with respect to domestic/international use of the same aircraft. Comparison of average stage lengths shows good agreement except for the overall average, a result of the underrepresentation of the turboprop aircraft.

Passenger Assignment Process

The objective of this process is to convert the forecasted O-D passenger demand into passenger loadings on each nonstop route segment. This conversion requires that the distribution of direct and indirect (connecting) passengers be determined for each O-D city-pair, and therefore a complete picture of the passenger flow among cities must be constructed. A major complication in describing this system is the fact that only 600 of the approximately 45,000 city-pairs in the system have been modeled due to computational limitations. An additional complication arises from the nature of available O-D and segment data, some of which are subdivided by airline and must therefore be aggregated for purposes of this model.

To facilitate understanding of the passenger assignment process, which is complex and difficult to describe, the base-year passenger flow analysis diagrammed in Fig. 4 has been constructed with vertical and horizontal symmetry. The flow proceeds vertically downward, starting with O-D demand, Q_{OD}, which is computed independently of the assignment process for each city-pair* by the demand and modal-split models. At the middle of the diagram, this O-D flow has been converted to a quantity representing the number of coupons written, C, and at the bottom the passengers on each route have been assigned to arrive at the desired quantity, the number of nonstop passengers, Q_{NS}. Horizontally, the flow is divided into three basic parts, with the left side describing the flow of direct passengers on routes represented in the 600 city-pair sample, the center describing the assignments of connecting passengers to or from other routes which are also in the forecast sample, and the right side describing the assignments of connecting passengers to or from routes which are not in the sample.

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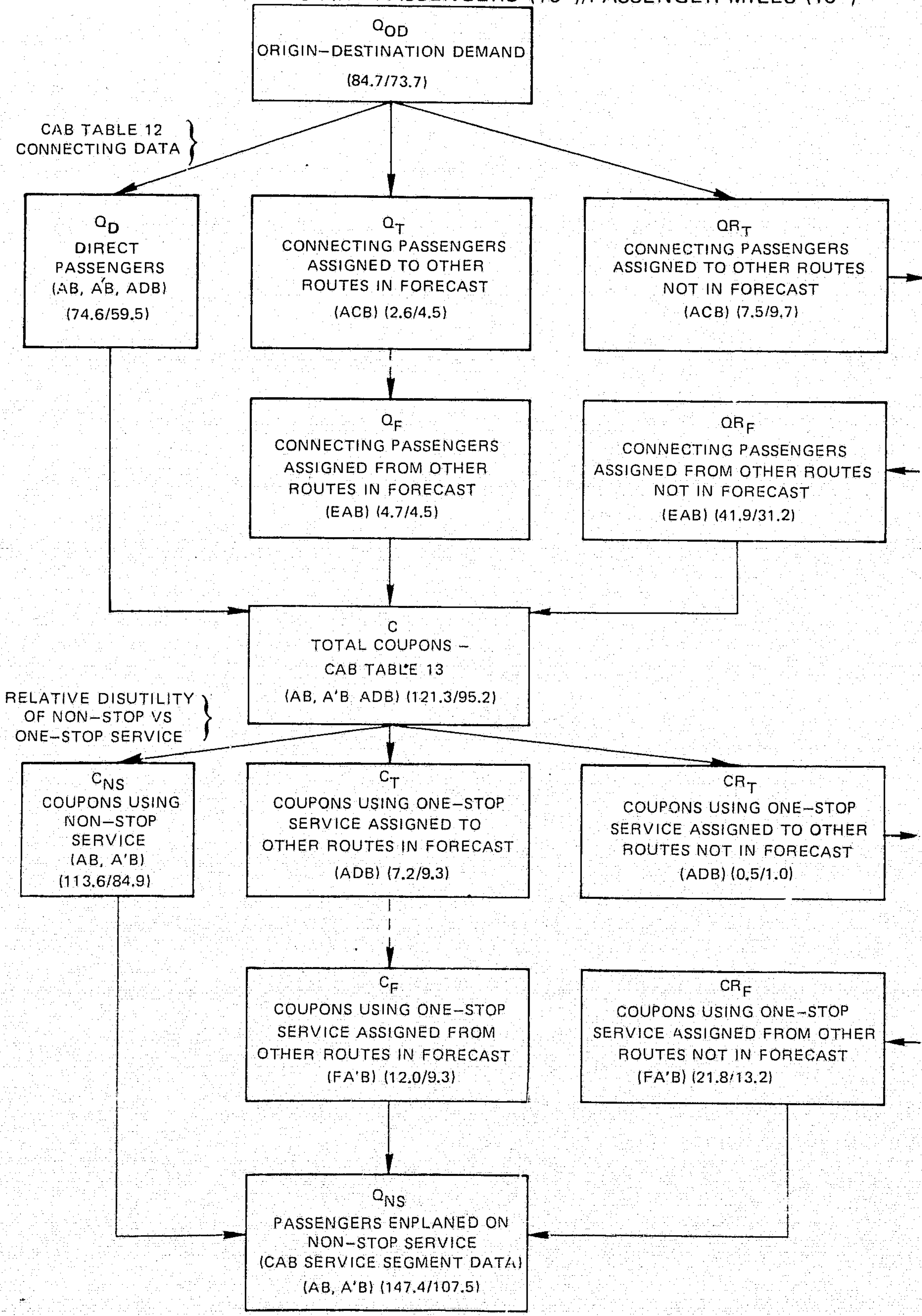
* Although the process described in Fig. 4 is carried out for each of the 600 city-pairs in the sample, the data shown in each box refer to totals for all 600 city-pairs.

FIG. 4

PASSENGER FLOW PROCESS FOR BASE YEAR – CITY PAIR AB

ITINERARIES REFER TO FIG. 5

DATA IN PARENTHESES ARE PASSENGERS (10^6)/PASSENGER MILES (10^9)



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The O-D demand, Q_{OD}, is divided into direct (Q_D) and connecting passengers (Q_T and QR_T) as given in Table 12 of the CAB Origin-Destination Survey. Possible routings for these passengers are indicated in parentheses in Fig. 4; these routings are shown in Fig. 5 to illustrate various types of flights serving city-pair A-B. The direct passengers (Q_D) can use nonstop flights (A-B or A'-B) or one-stop flights (A-D-B); the connecting passengers may follow itineraries involving other city-pairs in the 600 city-pair forecast (Q_T) or may follow itineraries involving city-pairs not in this forecast (QR_T). The connecting passengers assigned from other city-pairs in the forecast to a particular city-pair form the quantity Q_F. An example would be O-D passengers from city-pair E-B connecting at A and hence assigned to route A-B (and also E-A if included in the forecast). The value of Q_F for any route A-B is determined from the appropriate values of Q_T for other city-pairs (such as E1-A-B, E2-A-B, etc.) which assign passengers to A-B, as indicated by the broken arrow in Fig. 4. Similarly, the residual assignments from routes not in the forecast (QR_F) result from the various values of QR_T; however, QR_F cannot be computed directly unless all 45,000 city-pairs are considered. An indirect computation of QR_F is possible since the sum (Q_D + Q_F + QR_F) is tabulated in Table 13 of the O-D Survey as the total number of coupons, C.

The number of coupons, C, includes passengers using both nonstop and other direct service. However, an exact breakdown is not available, thereby requiring the use of an approximate algorithm. As a simplification, only nonstop and one-stop flights have been considered. The assignment of passengers to either nonstop or one-stop flights, which is explained in detail further on, is a computed allocation made on the basis of relative disutility, considering the total flight time and the schedule inconvenience associated with the service frequency. This computation results in assignment of all coupons to nonstop flights (C_{NS}) if the nonstop frequency is greater than about four per day (in each direction) and of most coupons to nonstop flights for nonstop frequencies between two and four. The coupons assigned to one-stop service can be assigned to routes which are either included (C_T) or not included (CR_T) in the forecast, as determined by the one-stop data taken from the OAG. (Note that the lower portion of Fig. 4 is entirely analogous to the upper portion, considering coupons instead of O-D passengers.) Summing the appropriate values of C_T for all 600 city-pairs, the value of C_F can be computed. The residual assignments from other routes (CR_F) cannot be found directly, but the total passengers enplaned on nonstop service (Q_{NS}) is available from the CAB Service Segment Data. Subtraction of (C_F + C_{NS}) from Q_{NS} gives CR_F.

PASSENGER FLOWS – CITY PAIR AB

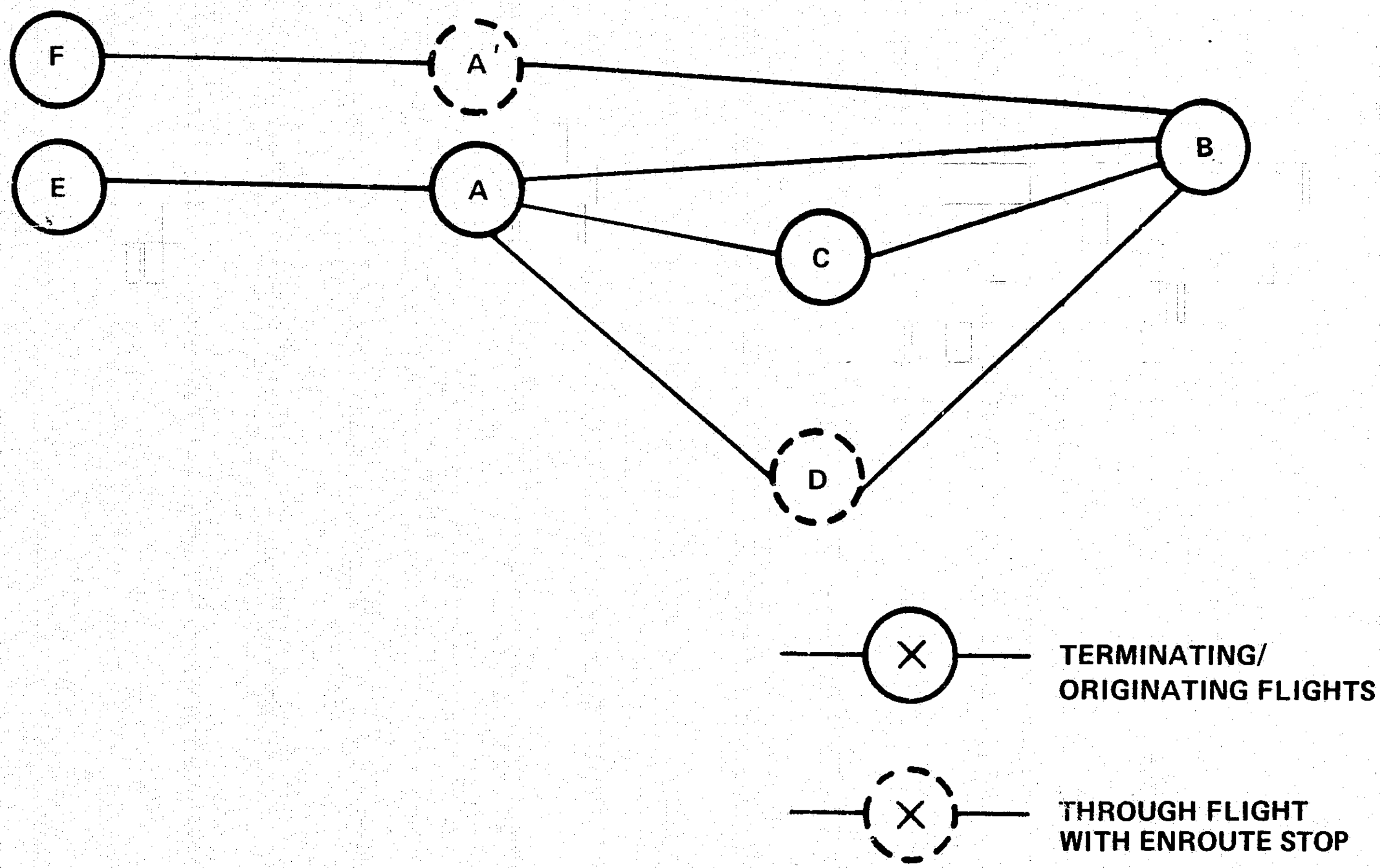


FIG. 5

Numerical values in Fig. 4 show total passengers and passenger-miles for the 600 city-pairs for each step of the assignment process. Note that the totals for O-D passengers and passenger-miles are increased by assignments made from other city-pairs. Thus, while the network includes only 64 percent of the total domestic passenger-miles on an O-D basis, the flights serving the network carry 86 percent of the total enplaned passenger-miles.

The net result of this process is to transform the O-D demand (Q_{OD}) into the number of passengers actually enplaned on nonstop flight segments (Q_{NS}). This process has been described in detail for the base year; however, for the forecast years a significant simplification is possible since it is not necessary to distinguish between passengers using one-stop flights and those making connections at intermediate points. For the purposes of this study, if an O-D passenger on route A-B is assigned to routing A-X-B, it makes no difference if he changes planes at X or uses a one-stop flight. The important consideration is that he occupies a seat on both the A-X and X-B routes.

The passenger assignment model used in the forecast years is shown in Fig. 6. The maximum total potential demand for nonstop service (Q) is found by adding together the forecasted O-D demand (Q_{OD}), the assignments from other routes (A_F), and a residual demand representing assignments from routes not in the forecast. The residual is found by increasing the base-year residual ($QR_F + CR_F$ in Fig. 4) by the growth in the total 600 city-pair O-D demand. Thus, the maximum demand for a city-pair is given by

$$Q = Q_{OD} + A_F + (QR_F + CR_F)_B \times \left[\frac{\sum Q_{OD}}{\sum Q_{OD_B}}\right]$$

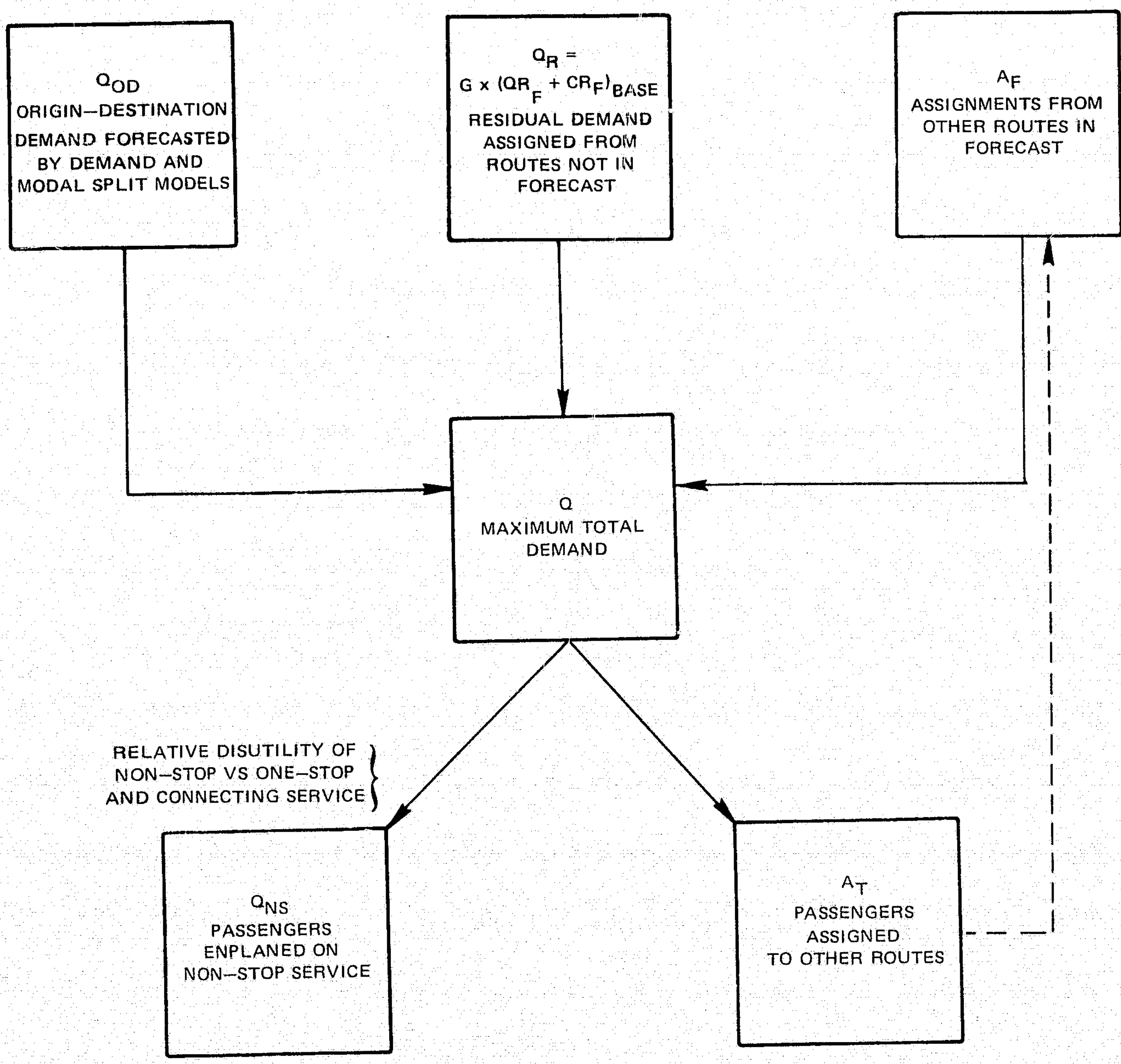
where the subscript B refers to base-year (1973) values.

In order to estimate fleet requirements for each route, it is necessary to estimate the number of passengers, Q_{NS}, who actually use the nonstop service.

$$Q_{NS} = \left[C_0 + C_1 \frac{F}{F_E}\right] Q \quad ,$$

where F is the total nonstop service frequency and F_E is the equivalent frequency of all the services offered (nonstop, one-stop, and connecting). The above expression divides the potential demand between nonstop and other service based on the relative attractiveness of each alternative, as measured by its equivalent frequency. The constants C_0 and C_1 are calculated from base-year data as described below and are unique to each city-pair.

PASSENGER ASSIGNMENT MODEL FOR FORECAST YEAR



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The equivalent frequency is calculated by considering the schedule inconvenience and travel time penalties associated with each type of service. The schedule inconvenience function, T_{sched}, is part of the modal-split model and relates the service frequency to an equivalent time which is then added to the travel time and used in computing the trip disutility. (This is discussed more fully in the appendix dealing with the demand and modal-split models.) For each city-pair, the base-year one-stop and connecting frequencies were added together to form the total additional frequency ΔF_B; for the forecast years, this additional frequency is assumed to grow at the same rate as the total number of nonstop flights in the 600 city-pair network. Thus,

$$\Delta F = \Delta F_B \times \left[\frac{\sum F}{\sum F_B}\right]$$

In addition, the average time penalty, ΔT, associated with the additional frequency was found by averaging together the block time penalty (relative to nonstop service) of each one-stop flight, and a nominal penalty of 1.6 hours for each connection. The equivalent nonstop frequency is determined from the actual nonstop frequency, F, and the additional service characteristics, ΔF and ΔT, by

$$F_E = \text{MAX} \left\{ F,\ T_{sched}^{-1}\left[T_{sched}(F+\Delta F) + \frac{\Delta F x \Delta T}{F+\Delta F}\right]\right\}$$

In this expression, the schedule inconvenience of the total available frequency $(F + \Delta F)$ is added to the average time penalty, and this total time is then converted back to an equivalent frequency. Since the time penalties associated with one-stops and connections could more than offset the convenience of their higher frequencies, it is necessary to check that F_E is not less than F. The equivalent frequency, F_E, is used along with the nonstop block time in computing the air disutility in the modal-split calculation. The relationship between the frequency ratio, (F/F_E), and the nonstop frequency, F, is illustrated in Fig. 7 for two typical situations--four one-stop flights/day each with a 1.0-hour time penalty, and ten connections/day, each with a 1.6-hour penalty. Although each city-pair has its own unique one-stop and connecting service, all have a similar relationship between F and F_E. F_E equals F when F is greater than about three to five. Also, from the above equation, F_E would be about 2.0 even when F = 0.

The relationship between (Q_{NS}/Q) and (F/F_E) is shown in Fig. 8 for three possible situations. For 249 city-pairs, there was sufficient nonstop service in 1973 that $(F/F_E)_B$ was unity. For these high-frequency city-pairs, it is assumed that (Q_{NS}/Q) will retain its base value in the forecast years

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EQUIVALENT FREQUENCY

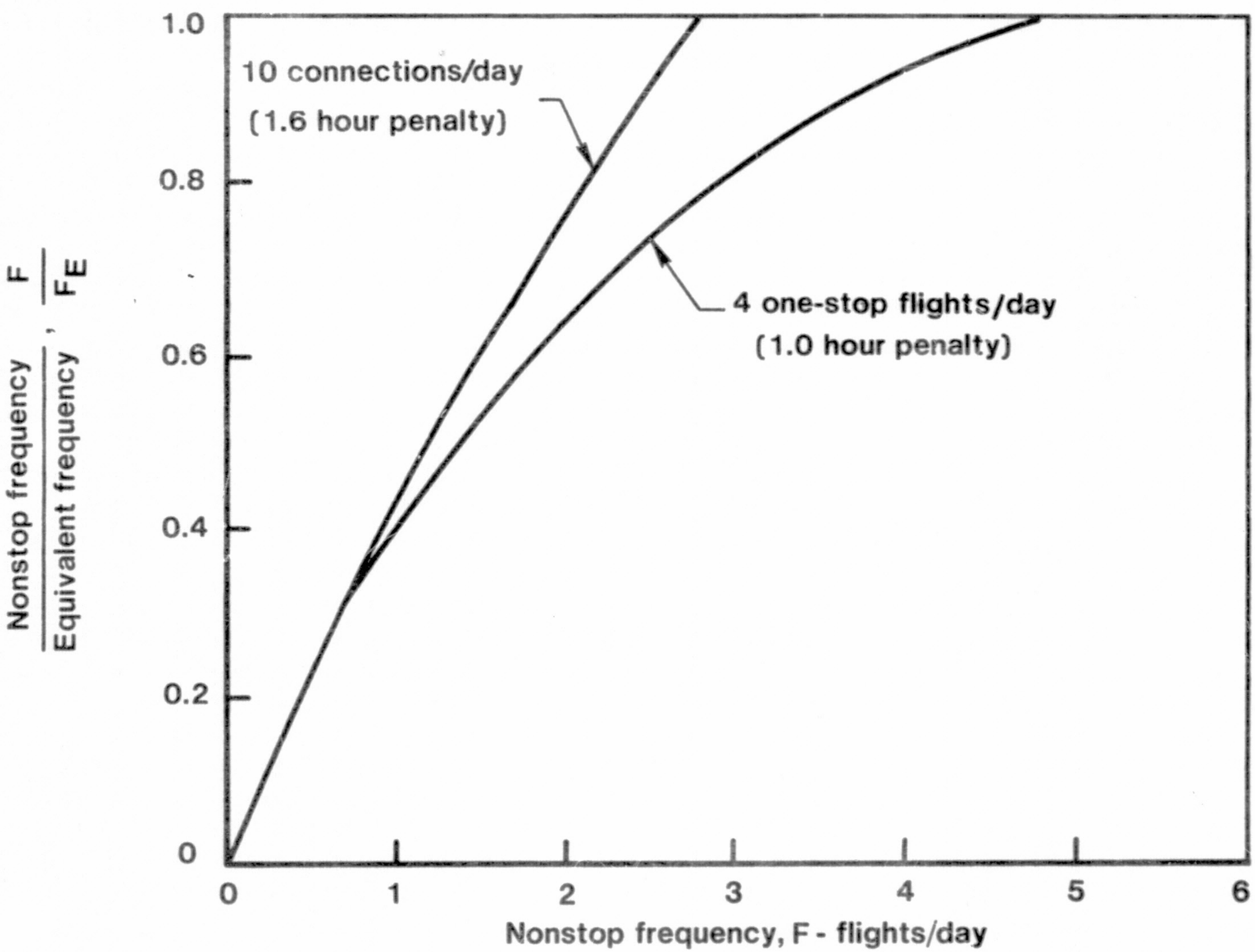

FIG. 7

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NONSTOP PASSENGERS

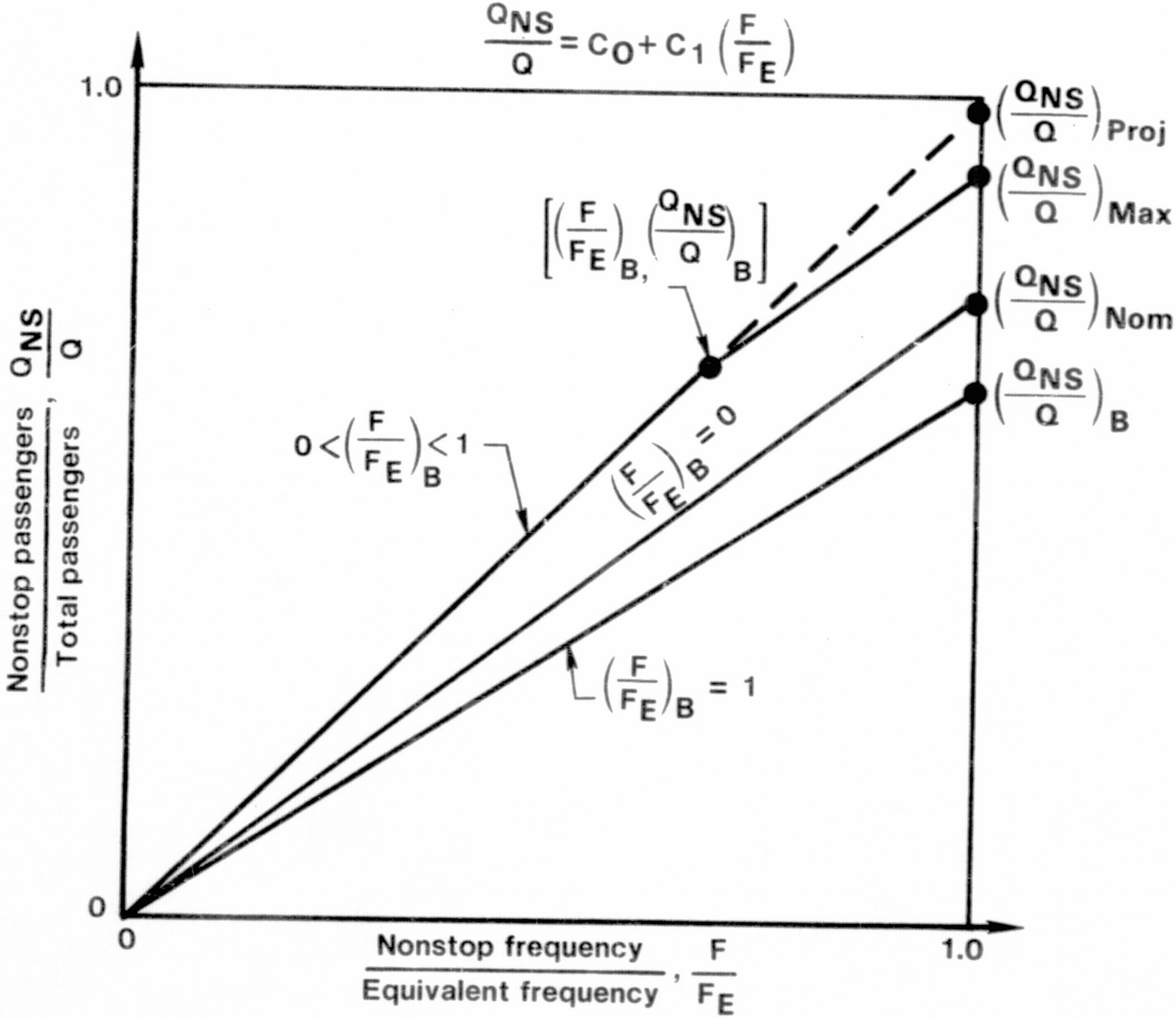

FIG. 8

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as long as (F/F_E) remains at unity. If F should decline sufficiently so that it falls below the equivalent frequency, which is unlikely, then linear interpolation is used. Thus, the number of passengers using nonstop service on high-frequency city-pairs is given by

$$Q_{NS} = \left(\frac{Q_{NS}}{Q}\right)_B \left(\frac{F}{F_E}\right) Q$$

where (F/F_E) is generally 1.0.

It was observed that the values of $(Q_{NS}/Q)_B$ for the 249 high-frequency city-pairs decline as distance increases. This presumably occurs because longer trips are more likely to involve multiple destinations. Thus, even though ample nonstop service exists, some travelers (about 15 percent on transcontinental routes) stop at intermediate points and are thus assigned to other routes.* This relationship is used to establish a nominal maximum value for (Q_{NS}/Q) for the 117 city-pairs which did not have nonstop service in 1973 (i.e., $(F/F_E)_B = 0$). As nonstop service is introduced on these routes, the nonstop passengers are given by interpolation as

$$Q_{NS} = \left(\frac{Q_{NS}}{Q}\right)_{Nom} \left(\frac{F}{F_E}\right) Q$$

where

$$\left(\frac{Q_{NS}}{Q}\right)_{Nom} = 0.994 - 0.052x(\text{distance}/1000)$$

Finally, for the remaining 234 city-pairs having low-frequency levels such that $0 < (F/F_E)_B < 1.0$, a two-segment linear interpolation is used. For frequencies below those of the base year,

$$Q_{NS} = \frac{(Q_{NS}/Q)_B}{(F/F_E)_B} \left(\frac{F}{F_E}\right) Q.$$

* In collecting data for the O-D Survey, the CAB ignores the length of time spent at each enroute point. Thus, the farthest point on a round-trip itinerary is the "destination", and intermediate points are assumed to be connecting points, even though they may in fact be additional destinations.

In the more likely event of an increase in frequency, the maximum value of (Q_{NS}/Q) is found by a weighted average between a projection of the base-year data,

$$\left(\frac{Q_{NS}}{Q}\right)_{Proj} = \frac{(Q_{NS}/Q)_B}{(F/F_E)_B}$$

and the nominal maximum defined above. Thus,

$$\left(\frac{Q_{NS}}{Q}\right)_{Max} = \left(\frac{Q_{NS}}{Q}\right)_{Proj} \left(\frac{F}{F_E}\right)_B + \left(\frac{Q_{NS}}{Q}\right)_{Nom} \left[1 - \left(\frac{F}{F_E}\right)_B\right]$$

$$= \left(\frac{Q_{NS}}{Q}\right)_B + \left(\frac{Q_{NS}}{Q}\right)_{Nom} \left[1 - \left(\frac{F}{F_E}\right)_B\right]$$

(Note that $(Q_{NS}/Q)_{Max}$ is not allowed to exceed 1.0.) This weighting places more emphasis on the projected value when $(F/F_E)_B$ is closer to 1.0, and relies more heavily on the nominal value when the base-year frequency is very low. Thus, the number of nonstop passengers is given by

$$Q_{NS} = \left\{ \left(\frac{Q_{NS}}{Q}\right)_B + \left[\frac{\left(\frac{Q_{NS}}{Q}\right)_{Max} - \left(\frac{Q_{NS}}{Q}\right)_B}{1 - \left(\frac{F}{F_E}\right)_B}\right] x \left[\left(\frac{F}{F_E}\right) - \left(\frac{F}{F_E}\right)_B\right] \right\} Q$$

Referring back to Fig. 6, those passengers who do not use the nonstop service are assigned to other routes using the same assignment pattern as determined in the base year. The number of passengers assigned to a particular route is given by:

$$A_{T_j} = T_j \, (Q - Q_{NS})$$

where

$$T_j = \left[\frac{Q_{T_j} + C_{T_j}}{\sum(Q_{T_k} + C_{T_k}) + QR_T + CR_T}\right]_B = \left[\frac{A_{T_j}}{Q - Q_{NS}}\right]_B$$

Thus, the level of assignments to other routes will vary (presumably decrease) in the forecast years as nonstop service is increased, but the pattern of those assignments will remain the same. By carefully modeling the base-year system with respect to routing patterns and the use of nonstop service frequency, it is possible to make forecasts that reflect the effects of growth while preserving the fundamental structure of the existing system.

The assignment of passengers from one route to another requires that the city-pairs be processed in such an order that assignments are always made "ahead" to routes not yet analyzed. The determination of such an ordering required the construction of a fairly elaborate computer program. This program also processed the other base-year data and prepared an extensive data base for use by the passenger and fleet assignment model. These data included the process ordering and base values of (Q_{NS}/Q), (F/F_E), T_j, ΔF, ΔT, and $(Q_{R_F} + C_{R_F})$.

Aircraft Assignment Process

In the discussion above, it was shown that the number of passengers enplaned on each route depends on the nonstop frequency except on those routes where $(F/F_E) = 1.0$. Since the flight frequency depends on the number of passengers, the expressions above for Q_{NS} must be solved simultaneously with those given below for F. Furthermore, the entire passenger and aircraft assignment process must be completed for one city-pair before moving on to the next. The aircraft assignment algorithm assumes that aircraft in use on a particular route in the previous forecast year will remain in use (after adjustment for retirements) and that the remaining required capacity will be filled by a single new aircraft type appropriate to the option under study. Frequency and load factor considerations determine the type and number of aircraft chosen. Thus, abrupt changes in the air system are avoided.

Aircraft assignments are made sequentially for each route, the first step being to set minimum and maximum values on frequency. These limits are based on the total nonstop frequency in the previous year, F_0, and are graphically depicted in Fig. 9. They were estimated by judgment and adjusted to fit empirical evidence, as follows:

$$\text{for } F_0 < 8 \qquad \begin{aligned} F_{MIN} &= 1 + 0.875\ F_0 \\ F_{MAX} &= 8 + 1/2\ F_0 \end{aligned}$$

$$\text{for } 8 \le F_0 \le 16 \qquad \begin{aligned} F_{MIN} &= 2 + 3/4\ F_0 \\ F_{MAX} &= 8 + 1/2\ F_0 \end{aligned}$$

$$\text{for } F_0 \ge 16 \qquad \begin{aligned} F_{MIN} &= 2 + 3/4\ F_0 \\ F_{MAX} &= F_0 \end{aligned}$$

FREQUENCY LIMITS USED IN AIRCRAFT ASSIGNMENT ALGORITHM

[① - ④ : Assignment preference rank]

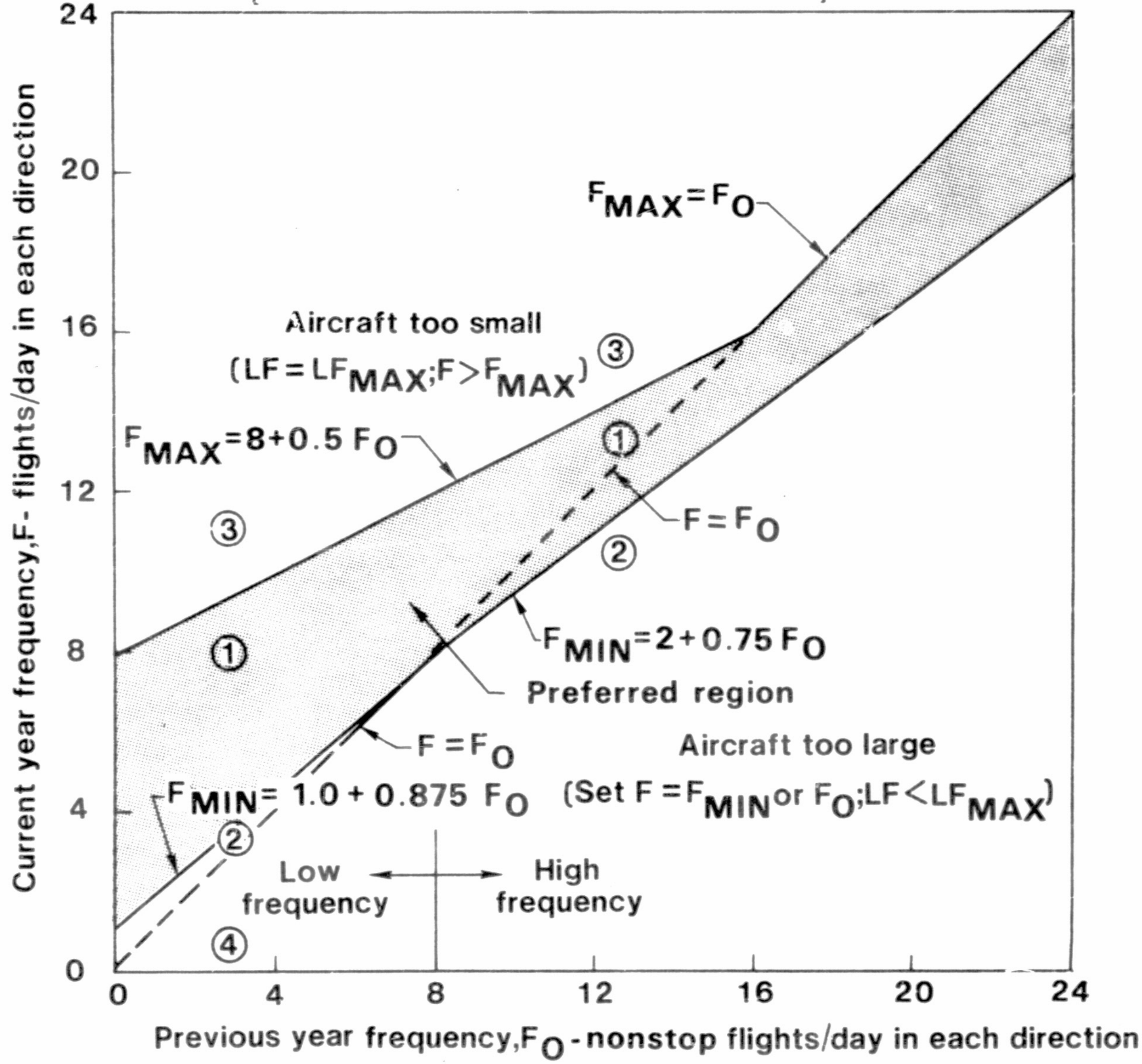

FIG. 9

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Relative to the previous year, frequency is allowed to increase (but cannot decrease, i.e. $F_{MIN} > F_O$) on low-frequency routes ($F_O < 8$); on high-frequency routes ($F_O > 16$), no frequency increase is allowed, i.e., $F_{MAX} = F_O$, but a decrease of from 12 1/2 percent to 25 percent is permissible. These criteria were developed to increase service where needed while at the same time restraining overall frequency growth to avoid congestion at the large hubs.

A maximum load factor, LF_{MAX}, is set at 60 percent for routes under 1000 miles and Hawaiian routes, and 56 percent for routes over 1000 miles. These values reflect both the desired 58 percent overall system load factor (average of the two values) and historic variations in load factor with stage length.*

The total frequency provided by existing aircraft on each route, F_R, is determined from the previous-year frequencies less retirements. Thus,

$$F_R = \Sigma R_i F_i$$

where the summation is over all aircraft types in use on the particular route, and R_i represents the retirement factor, as discussed below, associated with each aircraft type. If F_R is greater than F_{MIN}, no new aircraft are needed, provided the load factor is less than LF_{MAX}. (This occurs on routes with very low base-year load factors.) The load factor is given by:

$$LF = Q_{NS}/S_R ,$$

where S_R is the total of all seats provided by the F_R existing flights. If new aircraft are needed, the "in-production" aircraft type meeting range requirements and having the lowest 15 percent return-on-investment load factor (LF_{ROI}), as provided by UAL, at the given stage length is considered first. The new aircraft frequency F_N, is set to ($F_{MIN} - F_R$), and the load factor

$$LF = Q_{NS}/(S_R + S_N F_N)$$

* These load factor assumptions are operative only when the target load factor for the entire system is the nominal 58 percent figure adopted for the study. For special scenarios in which the system load factor was specified to be higher, the assumed values were increased correspondingly.

is calculated, where S_N is the seating capacity of each new aircraft. If $LF < LF_{MAX}$, the aircraft is too large. If $LF > LF_{MAX}$, the value of F_N at which $LF = LF_{MAX}$ is determined. (Note that if the total frequency, $F = F_N + F_R$, is less than about 4, an iterative trial-and-error procedure involving the simultaneous solution of the expressions for Q_{NS} and LF given above is required.) If $F > F_{MAX}$, when $LF = LF_{MAX}$, the aircraft is too small; if $F < F_{MAX}$, the aircraft is acceptable.

The process described above is repeated, with aircraft types considered in order of increasing LF_{ROI}, until an acceptable assignment is made. If no acceptable aircraft is found, a selection is made from among the rejected aircraft according to the following priorities:

$F_O > 8$
(1) Preferred frequency range ($F_{MIN} < F < F_{MAX}$); if none,
(2) Select best large aircraft (highest $LF < LF_{MAX}$ with F set to F_{MIN}); if none
(3) Select best small aircraft (lowest $F > F_{MAX}$ with $LF = LF_{MAX}$).

$F_O < 8$
(1) Preferred frequency range ($F_{MIN} < F < F_{MAX}$); if none,
(2) Select aircraft with highest F, where $F_O < F < F_{MIN}$; if none,
(3) Select best small aircraft (lowest $F > F_{MAX}$ with $LF = LF_{MAX}$); if none,
(4) Select best large aircraft (highest $LF < LF_{MAX}$ with F set to F_O).

These priorities are shown graphically in Fig. 9. Note that the total frequency is forced to be at least F_{MIN} ($F_O > 8$) or F_O ($F_O < 8$) even if a load factor less than LF_{MAX} results. Conversely, the load factor is never allowed to exceed LF_{MAX}, even if this requires a frequency greater than F_{MAX}.

For those routes which had no nonstop service in the previous forecast year ($F_O = 0$), a different procedure is used. For each in-production aircraft type, the frequency, F, is set to 0.5* and the resulting load factor LF is computed. If $LF < LF_{ROI}$, the aircraft is unacceptable; if $LF > LF_{ROI}$ F is increased until $LF = LF_{ROI}$. This process is repeated for all available aircraft types and the one offering the highest frequency with $LF = LF_{ROI}$ (if any) is selected. In the above procedure, LF_{MAX} is used instead of LF_{ROI} whenever $LF_{ROI} > LF_{MAX}$ (i.e., new routes should not have a higher load factor requirement than existing routes).

* Throughout the assignment process, frequencies are allowed to assume noninteger values. This is appropriate since the frequencies represent averages over an entire year, during which there could be seasonal, day-of-week, and directional variations as well as growth-induced increases.

The aircraft assignment algorithm tends to favor small aircraft for low-density routes and large aircraft for high-density routes. Use of ROI as a criterion in the assignment process is proper only when more than one aircraft type is appropriately sized for a particular route.

It is believed that this algorithm is a reasonable model of airline behavior in a competitive environment. As a test of this hypothesis, the algorithm was used to "forecast" the 1973 fleet. In this test, 1973 was considered both the base and the forecast year, with no demand growth. The entire fleet of each in-production aircraft (B-747, DC-10/L-1011, B-727-200, B-737-200, DC-9-30) was "retired", but all other types were retained. The algorithm was then used to assign the in-production aircraft. For this test, the range between F_O and F_{MAX} and F_{MIN} was narrowed to force the frequencies as close as possible to F_O; also, values of LF_{ROI} reflecting 1973 fuel costs and seating capacities were used. A trial-and-error variation of LF_{MAX} was performed until the system load factor was close to the 1973 value.

Overall results of this test case, as shown in Table III, are quite good. Perfect agreement for each sub-fleet would not be expected because the wide range in actual route load factors is not reflected by the algorithm. Furthermore, the early introduction dates of some aircraft relative to competing types (e.g., B-747 before DC-10/L-1011) explains the overestimates in their fleets.

Aircraft Retirement Algorithm

The forecast period of this study extends to the year 2000, or 27 years from the base year, 1973. Since this period exceeds the expected service lifetime of a typical commercial aircraft fleet, it is necessary to devise a retirement algorithm which permits removal of old airplanes. Particularly in the baseline case, where models introduced as early as the late 1960's are assumed to accommodate growth out to the end of the century, the retirement process must be specified in detail so that the required number of new aircraft in each forecast year can be determined accurately.

In the fleet assignment process, the forecast years are taken up in sequence: 1973, 1980, 1985, 1990, and 2000. Thus, the 1980 forecast requires knowledge of the disposition of aircraft in service in the base year, because the number and type of new airplanes to be assigned to each route will depend on the fraction of the 1973 fleet that has been retired.

TABLE III

USE OF AIRCRAFT ASSIGNMENT ALGORITHM TO
REPRODUCE 1973 FLEET

		Actual	Algorithm
600 City-Pair Fleet:			
In Production:	B-747	65	46
	DC-10/L-1011	100	147
	B-727-200	247	221
	B-737-200	87	79
	DC-9-30	172	200
Out of Production:		701	701
TOTAL		1372	1395
System Load Factor		51.2%	50.5%
Total Flights/Day		6615	6629

Similarly, the the 1985 forecast the retirements which take place between 1980 and 1985 will affect the 1985 fleet assignments. However, the dates of introduction of all of these airplanes must be accounted for in each year, since part of the original 1973 fleet may still be in operation in 1985.

The procedure for generating the retirement factors for in-production aircraft is illustrated in Fig. 10 for the Baseline DC-9-30 fleet as an example. Originally introduced in 1967, the fleet consisted of N_{73} airplanes in the base year. As with all aircraft in the study, the assumed aircraft lifetime, T_D, is 16 years. For simplicity, the buildup of the fleet between each pair of forecast years is approximated by a straight line. Thus, the time history of the base-year fleet is indicated by the shaded area labeled "Airplanes Introduced in the 1967-1973 Period". The 1973 fleet remains intact until 1983, at which time retirements commence exactly in keeping with the 1967-1973 introductions. In Fig. 10, the portion of the 1973 fleet still in service in the first forecast year, 1980, is designated N_{73}'.* Since none of the 1973 fleet has been retired by 1980, the new 1980 fleet assignments determined by the fleet assignment model, N_{N73-80}, are added to N_{73}' to get the total in 1980. However, in the next forecast period, 1980 to 1985, retirements of the base-year fleet begin. Thus N_{80}', the 1980 fleet still in service in 1985, consists of all the new airplanes introduced in the previous period plus a fraction of the base-year fleet.

The number of new DC-9-30 aircraft required in 1985 is small, thereby causing a decline in the total fleet from 1980 to 1985. In the next five-year period, 1985-1990, fleet size at the DC-9-30 continues to decline. as retirement of the base-year fleet is completed. In 1990, the number of required new aircraft, N_{N85-90}, is somewhat larger than N_{N80-85} due, in part, to the fact that the base-year fleet is gone and retirements of the next sub-fleet have begun. Continuing the process to the last forecast year, 2000, it is seen that all aircraft have been retired except a small portion of those introduced between 1980 and 1985 and the aircraft added between 1985 and 1990. These airplanes, which total N_{90}', comprise the entire carryover fleet of DC-9-30's in the last forecast year.

The example shown in Fig. 10 illustrates the basic approach of the retirement algorithm. Aircraft are introduced in discrete quantities

* Since none of the in-production models in this study were introduced before 1967, and $T_D \geq 13$, $N_{73}' = N_{73}$ in every case; i.e., the 1980 retirement factor is zero.

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EXAMPLE OF RETIREMENT ALGORITHM

BASELINE CASE

DC–9–30

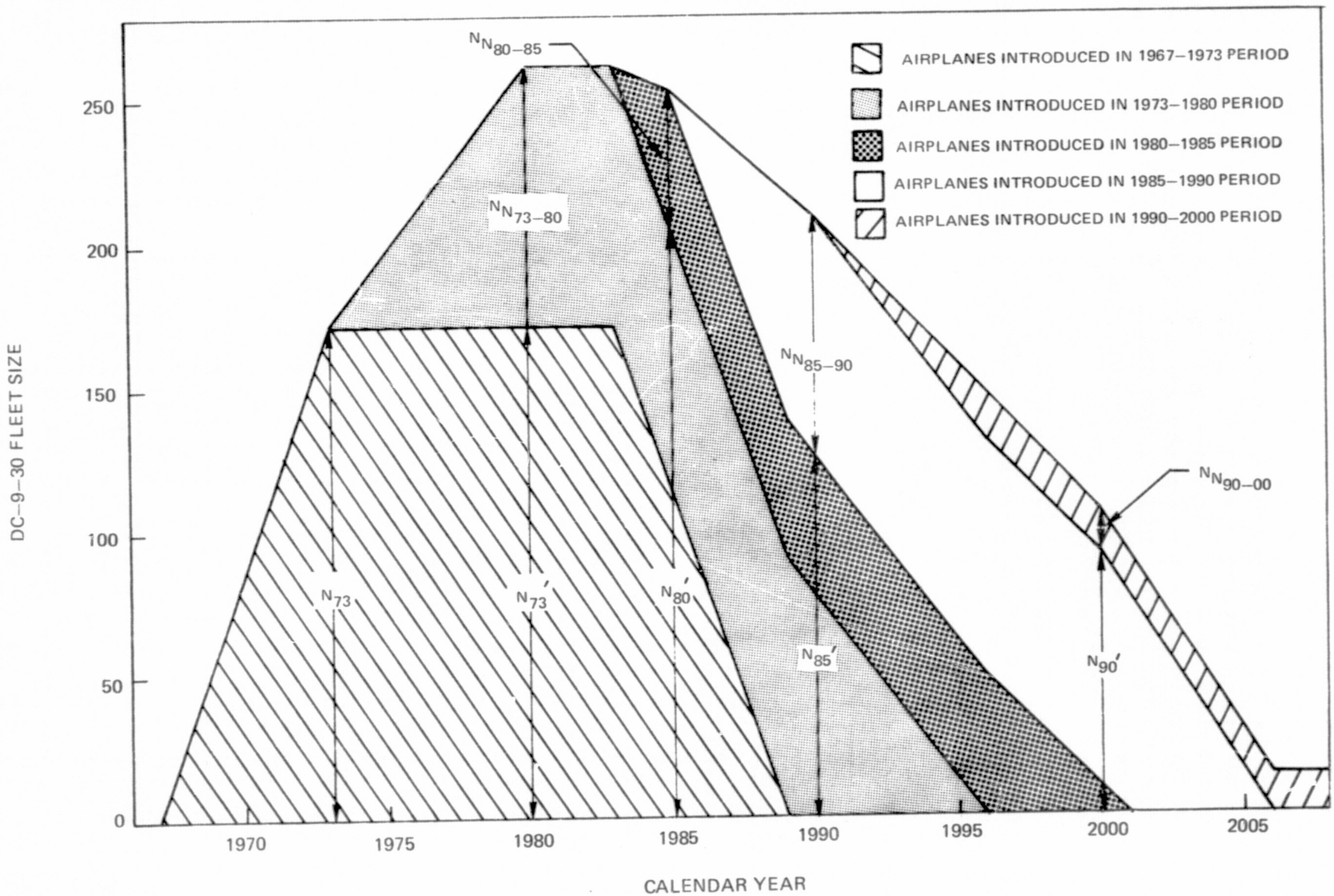

FIG. 10

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corresponding to the buildup of the fleet between forecast years. Based on an assumed lifetime, the retirements proceed as "reflections" of the introduction segments. Thus, the important parameters in the derivation of the retirement factor equations are the introduction year, Y_o; the service lifetime, T_D; the forecast-year fleets: N_{73}, N_{80}, N_{85}, N_{90} and N_{00}; and the new airplanes introduced in each period: N_{N73-80}, N_{N80-85}, and N_{N85-90}, and N_{N90-00}.

Using the index i to represent the forecast year, and the symbol Δ for the period between i and the next period $(i + \Delta)$, the retirement factor is defined as the fraction of the fleet in year i which was retired between i and $i + \Delta$.

$$R_{\left(\frac{i+\Delta}{i}\right)} = 1 - \frac{N_i'}{N_i}$$

The fleets N_i' are determined by summing the remaining airplanes from each group introduced in a previous period. These terms are always less than or equal to the total airplanes introduced in that period and greater than or equal to zero. The resulting retirement equations are as follows:

$$R_{80/73} = 1 - \frac{\left[\dfrac{T_D - 7}{73 - Y_o}\right] N_{73}}{N_{73}} = 0$$

$$R_{85/80} = 1 - \frac{\left[\dfrac{T_D - 5}{7}\right] N_{N73-80} + \left[\dfrac{T_D - 12}{73 - Y_o}\right] N_{73}}{N_{80}}$$

$$R_{90/85} = 1 - \frac{\left[\dfrac{T_D - 5}{5}\right] N_{N80-85} + \left[\dfrac{T_D - 10}{7}\right] N_{N73-80} + \left[\dfrac{T_D - 17}{73 - Y_o}\right] N_{73}}{N_{85}}$$

$$R_{100/90} = 1 - \frac{\left[\dfrac{T_D - 10}{5}\right] N_{N85-90} + \left[\dfrac{T_D - 15}{5}\right] N_{N80-85} + \left[\dfrac{T_D - 20}{7}\right] N_{N73-80} + \left[\dfrac{T_D - 27}{73 - Y_o}\right] N_{73}}{N_{90}}$$

where the bracketed terms are not permitted to exceed the range zero to 1.0.

Each airplane type is described by particular values of the quantities Y_o and N_{73} which are required as inputs to calculate the initial retirement factor. (T_D is 16 years for all aircraft in the study.) These quantities are summarized in Table IV for the baseline airplanes. Introduction years for the retrofit, derivative, and new airplanes are also given in the table.

Out-of-Production Aircraft

Out-of-production aircraft include early models of narrow-body airplanes including the DC-9, B-727, DC-8, B-707, B-720 and CV-880, as well as one wide body, the B-747-100. Although these airplanes comprised a sizable fraction of the fleet serving the 600 city-pairs in 1973 (51 percent), many were due for retirement. Even between 1973 and the present (end of 1975), almost 100 of these early models have left domestic fleet service. Since out-of-production aircraft fleets can only decline, their retirement schedules were based on the method described in Ref. 10, where service lifetime was correlated with maximum fleet size. Based on this correlation the early-model narrow-body fleets are expected to be reduced to negligible sizes by the mid-1980's.*

Integrated Forecasting Model

The aircraft assignment algorithm was combined with the passenger flow algorithm described above and the existing demand and modal-split models to construct a complete forecasting program. In making a forecast, the program was run iteratively, with air O-D demand feeding into the passenger flow algorithm, and air frequencies, block times, and fares feeding back into the demand and modal-split program. Air frequencies are calculated directly in the aircraft assignment algorithm; block times correspond to the aircraft types assigned to each route and include an additive correction. These corrections were calculated for each route by subtracting the theoretical block time associated with the actual 1973 aircraft assignments from the scheduled block time taken from the Official Airline Guide; the corrections are both positive and negative, and are related to delays experienced at the airports involved.

* A summary of the nominal retirement schedule is given in the upper portion of Table XVI, on page 85, including an estimate of the 1975 fleets.

TABLE IV

SUMMARY OF AIRPLANE CHARACTERISTICS

Series	Airplane	Other Airplanes Represented	Capacity Seats (1980-2000)	Max* Stage St. Mi.	Year of Introduction, Yo	1973 Fleet Size (600 city-pair)	Flyaway** Cost $10^6	Flyaway Cost/Seat $/seat
Baseline: Out of Production	DC-9-10		70	1400	1966	46	4.100	58,600
	B-727-100		102	2010	1966	286	7.880	77,300
	DC-8-50	B-707-120B B-720B	139	3480	1961	139	8.600	61,900
	DC-8-62	B-707-320B	149	5640	1967	80	8.940	60,000
	DC-8-61		198	3470	1967	39	10.300	52,000
	DC-8-20	B-720, DC-8-30 CV-880	139	3035	1958	89	7.210	51,900
	Turboprop	CV-580/600, F-27, FH-227	45	300		13	0.930	20,700
Baseline: In Prod.	DC-9-30		92	1200	1967	172	5.150	56,000
	B-737-200		97	865	1970	87	5.620	57,900
	B-727-200		132	1795	1968	247	8.490	64,300
	DC-10-10	DC-10-40 L-1011-1	275	3240	1972	100	20.130	73,200
	B-747-200	B-747-100	386	5400	1970	65	29.100	75,400
Aero Retrofit	B-737-200R		97	865	1978	0	5.700	58,800
	DC-9-10R		70	1400	1978	0	0.080	--
	DC-9-30R		92	1200	1978	0	5.230	56,800
	B-727-100R		102	2010	1978	0	0.080	--
	B-727-200R		132	1795	1978	0	8.570	64,900
	DC-8-50R	B-707-120B B-720B	139	3480	1978	0	0.150	--
	DC-8-62R	B-707-320B	149	5640	1978	0	0.150	--
	DC-8-61R		198	3470	1978	0	0.150	--
	DC-8-20R	B-720, DC-8-30	139	3035	1978	0	0.150	--
	DC-10-10R	L-1011-1	275	3240	1978	0	20.410	74,200
	B-747-200R	B-747-100	386	5400	1978	0	29.380	76,100
Aero/Engine Retrofit	DC-8-20ER	B-720, DC-8-30	139	3035	1979	0	4.650	--
	DC-8-50ER	B-707-120B B-720B	139	3480	1979	0	4.870	--
	DC-8-61ER		198	3470	1979	0	4.870	--
	DC-8-62ER	B-707-320B	149	5640	1979	0	4.870	--
Derivative	DC-9-30D1		117	1200	1980	0	8.510	72,700
	DC-9-30D2		122	1600	1980	0	10.290	84,300
	B-727-300		156	2270	1979	0	13.900	89,100
	DC-10-10D		199	2540	1980	0	18.077	90,800
	DC-10-40D		327	3300	1980	0	35.879	109,700
	L-1011-LONG		407	2095	1980	0	26.920	66,100
	L-1011-SHORT		200	1855	1980	0	19.700	98,500
New Near Term	N80-200-I		200	1450	1980	0	17.284	86,400
	N80-200-L		200	2900	1980	0	19.706	98,500
	N80-400-L		400	2895	1985	0	30.471	76,180
New Far Term	N85-200		201	2940	1985	0	16.560	82,400
	N85-350		357	2940	1985	0	29.000	81,200
	N85-500		512	2940	1985	0	35.310	69,000
	N85-200F		200	1440	1985	0	16.775	83,900

* As supplied by UAL for 90% winter wind condition.

** Includes 15% for spares. For out-of-production Retrofitted Aircraft, tabulated cost is for retrofit only.

Fares are derived from a simplified ROI model. This model indicates that, to achieve 12 percent ROI, system revenues less system operating costs (including depreciation but excluding interest and income taxes) must equal 14.2 percent of the initial fleet investment. Implicit in the model are a 48 percent tax rate, 0.6 debt/equity ratio, 8 percent long-term interest rate, 16-year depreciation period, 10 percent salvage value, and non-aircraft investment equivalent to 15 percent of the aircraft investment. Operating costs are calculated from cost/hour data furnished for each aircraft type by UAL, DAC, and LCC. Revenues are calculated from a yield-vs-distance curve based on 1973 experience and adjusted for the Phase 9 fare adjustments provided by UAL, plus 10 percent for freight and mail revenues. Initial fleet investment is the total purchase price of the fleet, including spares. A revenue correction factor can then be calculated from

$$RCF = \frac{\text{COST} + 0.142 \times \text{INVESTMENT}}{\text{REVENUE}}$$

and applied to the base fares, which are 1973 fares adjusted for Phase 9 and appropriately discounted for business and personal travelers. Application of this technique to the 1973 system showed that revenues exceeded costs by an amount equivalent to 10.6 percent of the initial fleet investment, equivalent to 7 percent ROI; this is reasonably close to the actual 1973 ROI of 5 percent.

RESULTS OF DEMAND AND FLEET FORECASTS

The flow of aircraft data in this study was from the manufacturers (LCC and DAC), through UAL, to UTRC. An exception was the specification of characteristics for the baseline airplanes. Since most of these were present in their fleet, the data were supplied directly by UAL. Subsequent data generated by the manufacturers for derivatives and new designs were then adjusted by UAL to make them consistent with the cost and performance documentation of the baseline aircraft.

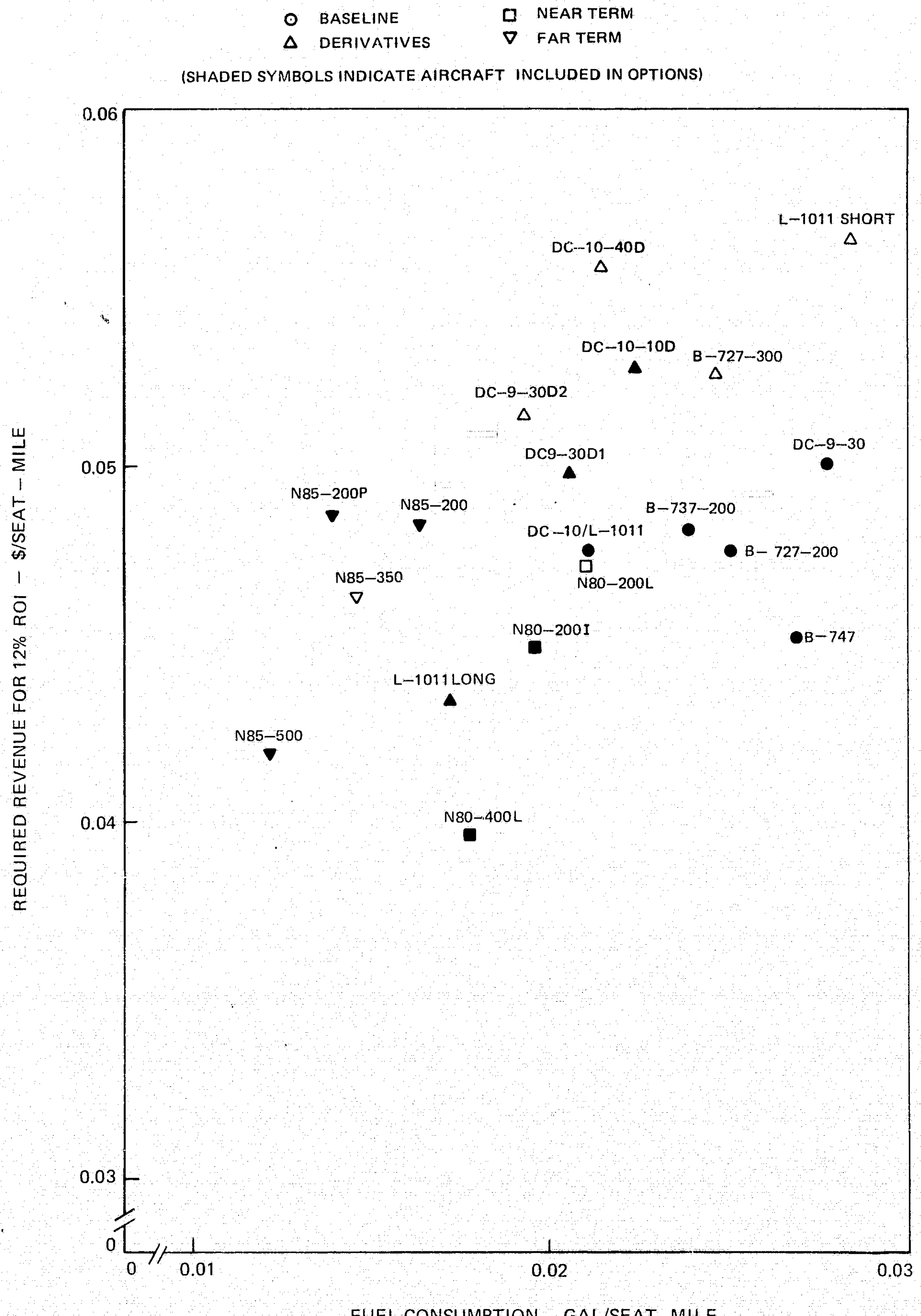
The cost and fuel consumption characteristics of the various aircraft which were provided in the study are important determinants of the results, since the fuel efficiency estimated for these airplanes is translated into fuel savings only if the airplanes are assigned to routes. Assignments are predicated on economic viability as determined in the UAL economic screening phase where the required passenger loadings for a 15 percent ROI were calculated. Therefore, the aircraft which comprise the resulting fleet in each fuel-conservation option are those which compete well in the critical 15 percent ROI screening. If these highly-ranked models are also fuel efficient, significant fuel savings will result from their assignment.

To provide an indication of the cost and fuel characteristics of the study airplanes, Figs. 11, 12 and 13 compare all airplanes in terms of required revenue vs. fuel consumption for stage lengths of 500, 1500, and 2500 st. mi. The revenue parameter, which was computed by UTRC, is intended to be a measure of competitive economic performance. It is not identical to the measure used by UAL in the economic screening, but it is similar in concept in that the UTRC parameter accounts for all operating costs (including fuel) as well as capital recovery for a 12 percent ROI. Use of a 12 percent ROI at all three stage lengths is not realistic in an operational sense and it should be stressed that ROI was not constant with stage length in the simulations. The use of a 12 percent ROI in Figs. 11 to 13 is a convenient assumption for the purposes of these airplane comparisons.

The comparisons include all airplanes considered for assignment in one or more options. The favorable parts of these diagrams are toward the lower left, i.e., low required revenue and low fuel consumption. Since some airplanes consume less fuel but require more revenue than their baseline competitors (e.g., DC-9-30D2 vs DC-9-30) these airplanes were never assigned to routes. On the other hand, an airplane such as the N85-500, a large, advanced-technology design, is superior in required revenue to the baseline wide bodies and also uses considerably less fuel. Therefore, the impact of this airplane can be expected to be great. In the discussion of the various fuel-conservation options, reference will be made to these diagrams and to Table IV, which summarizes basic aircraft features, to explain the resulting fleet assignments.

FIG. 11

REQUIRED REVENUE AND FUEL CONSUMPTION – 500 ST. MI. STAGE LENGTH



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REQUIRED REVENUE AND FUEL CONSUMPTION

1500 ST.MI. STAGE LENGTH

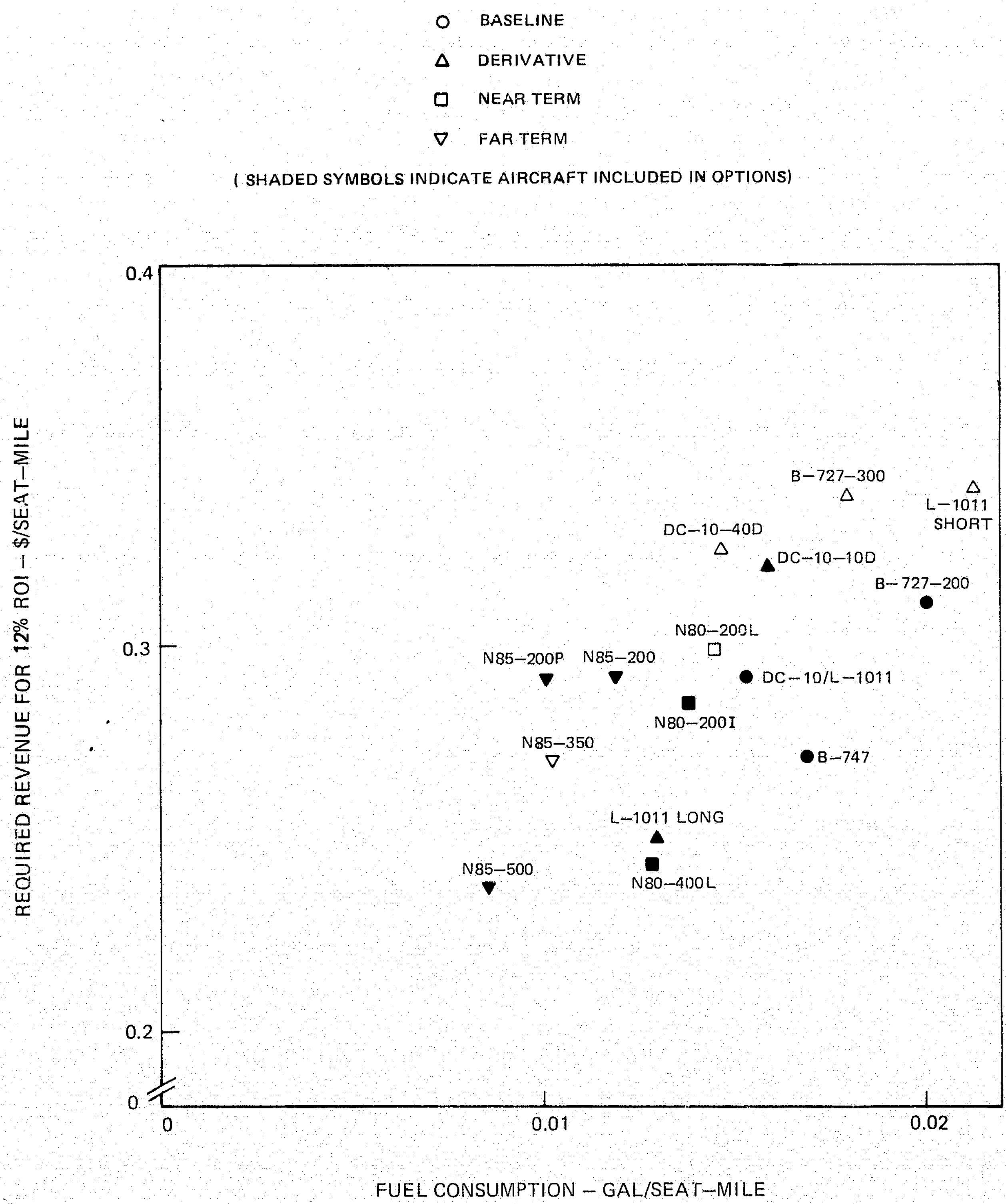

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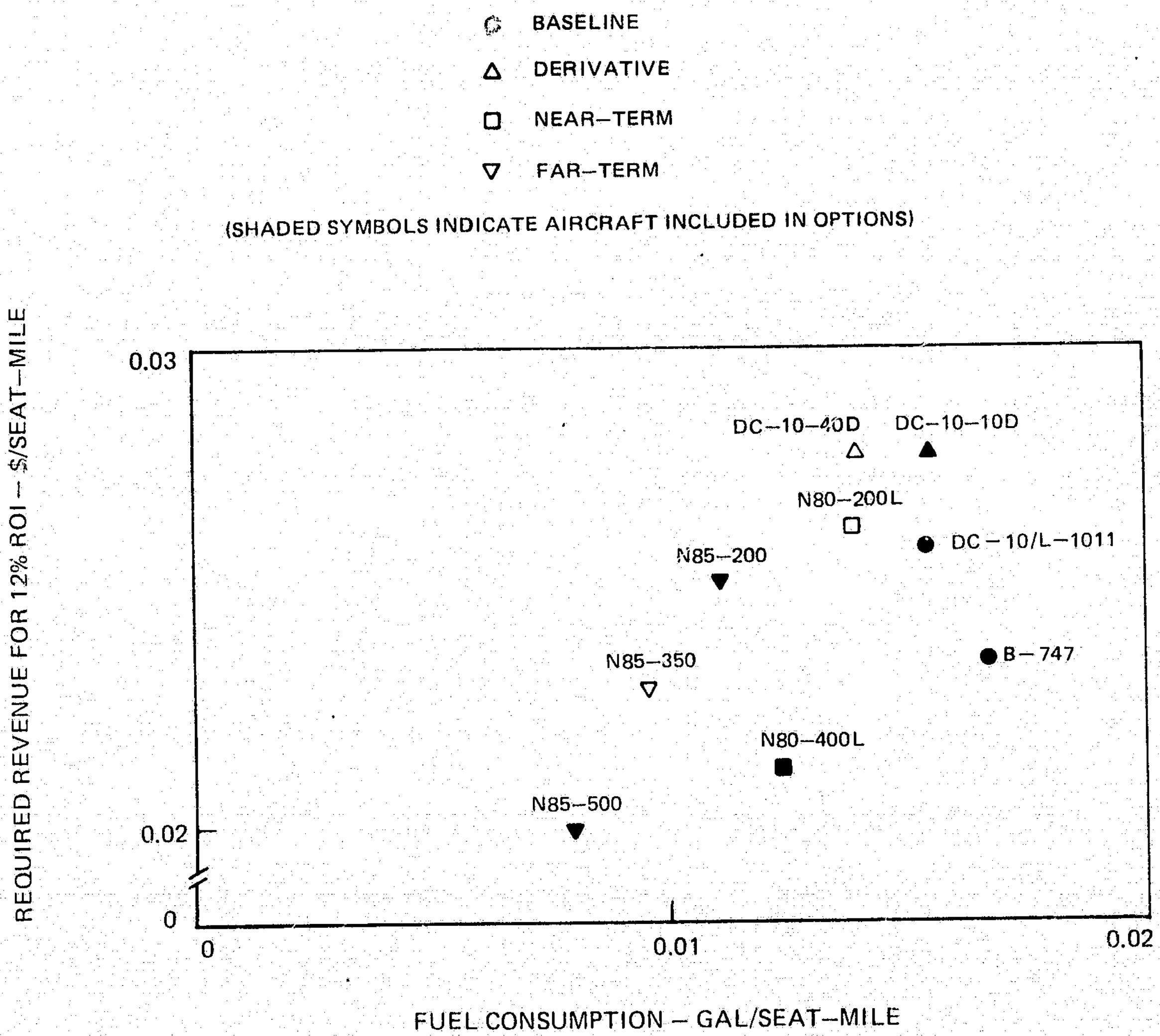
FIG. 13

REQUIRED REVENUE AND FUEL CONSUMPTION

2500 ST. MI. STAGE LENGTH



Before proceeding with descriptions of the individual options, it is important to understand the basic assumptions which are common to all the results which follow. At the outset of the study, certain ground rules agreed upon by the Contractors and the NASA Technical Monitor were documented in a Study Plan Report (Ref. 2). These ground rules are summarized here in abbreviated form in Table V in order that the results presented in this section can be interpreted properly.

Baseline Case

As explained in the INTRODUCTION, the purpose of the baseline case is to provide a datum by which to judge the amount of fuel saved in each fuel-conserving option. It includes the purely historical data for the base year (1973), as well as forecast data for the years 1980, 1985, 1990, and 2000. Thus, the baseline case represents a nominal evolution of the domestic system to the end of the 20th century, assuming that no new or derivative aircraft are available for service during that period. Growth in demand and fleet retirements are accommodated entirely by replacements from the list of in-production aircraft. Characteristics of these aircraft, and all other aircraft which appear in one or more options, are given in Table IV. Note that in the case of existing airplanes, important models not specifically treated in the study are represented by similar airplanes from the "in-production" and "out-of-production" listings.

A summary of baseline results for important system parameters is provided in Table VI. Note that, in all but the first column, the figures in the table are representative of the 600 city-pair system. Comparing the first two columns gives an indication of the accuracy of using this 600 city-pair system instead of the entire domestic U.S. as the basis for the forecast. In all important respects the representation is very high.

Since the 600 city-pairs comprise a predominantly urban portion of the total population, such characteristics as average income, travel propensity, air share of total O-D demand, business fraction, and air passengers carried nonstop, are higher in the sample than in the total U.S. Note also that the total U.S. figures are documented national statistics, whereas some of the 600 city-pair figures are calculated values. Thus, there are some minor inconsistencies, such as the slight over-representation of wide-body aircraft fleets, as explained earlier.

Of particular importance in this comparison are the representations of air demand by the 600 city-pair system. Since the city-pairs were selected on the basis of their contributions to air travel, they represent the air system to a much greater extent than travel by all modes. Whereas 62 percent

TABLE V

RECAT STUDY GROUND RULES

Seating

- 10%/90% first class/coach split
- 38-in. pitch first class; 34-in. coach
- Lower-level galley, no lounge in wide-body a/c
- Base year: 8-abreast DC-10/L1011; 9-abreast 747
- F'cst yrs: 9-abreast DC-10/L1011; 10 abreast 747

Cargo & Pass. Allowances

- Cargo 10% of revenue
- Passengers 200 lb., including baggage

Economic Parameters

- All costs in 1973 (base year) dollars
- Inflation 5%; discount rate 8%
- Spares allowance 15% flyaway cost
- New a/c breakeven production run 250 a/c
- Depreciation period 16 years

Operations Parameters

- Nominal load factor 58%
- Operating cost: DOC - ATA updated
  IOC - Lockheed

(Adjusted by UAL for service experience)

Hub Constraints

- For stage lengths under 800 mi, no wide-body a/c larger than DC-10/L1011 assigned to New York (LGA) and Washington (DCA)

Fares

- The following yield curve was used; incorporates effects of CAB Phase 9 adjustments. Base-year discount levels assumed for forecast years

Dist. (st.mi)	Base year ($/pass)	F'cst Yrs. ($/pass)
0	7.70	8.50
500	41.80	44.10
800	59.30	60.30
1000	70.80	69.20
1200	82.50	79.60
1600	101.90	96.80
2200	130.90	123.10
3300	154.00	144.30

- Hawaii yields are $0.0418/pass-mi

TABLE VI

BASELINE CASE SUMMARY

	Total U.S.* Domestic 1973	600 City-Pair Sample 1973	1980	1985	1990	2000	Avg. Growth Rate: 1973-2000
Total Population - 247 SMSAs (10^6 Persons)	209.6[3]	149.6	161.3	170.5	180.5	196.3	1.0%
Average Income - 247 SMSAs (1973 $/Person/Yr)	5041[3]	5242	6552	7426	8382	11,003	2.8%
Aircraft Fuel Price (1973 $/Gal)	0.1256	0.1256	0.30	0.30	0.30	0.30	
Travel Propensity - (Intercity Trips/Person/Yr)	2.10[4]	2.60	3.11	3.52	3.88	4.86	2.3%
O-D Passenger Demand - All Modes (10^6 Round Trips/Yr)	440.1[4]	139.6	182.7	221.5	260.4	358.3	3.6%
(10^9 Pass-Mi/Yr)	263.2[4]	119.2	164.7	204.3	245.4	352.6	4.1%
Air Share of Total O-D Demand (% of Round Trips)	15.5[4,12]	30.4	36.1	39.7	42.3	48.1	1.7%
(% of Pass-Miles)	43.9[4,12]	61.9	69.4	73.1	75.7	80.6	1.0%
Enplaned Air Passengers (10^6 One-Way Pass/Yr)	177.2[5]	147.4	228.4	303.6	379.7	593.7	5.3%
(10^9 Pass-Mi/Yr)	126.2[7]	107.5	168.8	224.1	280.5	436.1	5.3%
Avg. Growth Rate of Pass-Mi - O-D - All Modes (%/Yr)	-	-	4.7	4.4	3.7	3.7	-
- O-D - Air (%/Yr)	-	-	6.5	5.5	4.5	4.3	-
- Enplaned - Air (%/Yr)	-	-	6.7	5.8	4.6	4.5	-
Business Fraction of O-D Pass - All Modes (%)	20.5[4]	31.5	31.6	31.7	31.7	31.8	0
- Air (%)	54.4[4]	57.9	53.0	50.6	48.7	45.4	-0.9%
O-D Pass Trip Length - All Modes (St. Mi.)	299[4]	427	451	461	471	492	0.5%
- Air (St. Mi.)	893[4]	869	868	850	844	824	-0.2%
Routes with Nonstop Service	?	483	485	494	503	514	0.2%
Air Pass. Carried Nonstop (%)	63.5	89.0	91.4	92.6	93.3	94.1	0.2%
Fares Relative to 1973	1.000	1.000	0.995	0.957	0.950	0.937	-0.2%
Fuel Consumed by Air (10^6 Gal/Yr)	7799[7]	5808	6656	8440	10536	16400	3.9%
Avg. Growth Rate of Fuel Consumed by Air (%/Yr)	-	-	2.0	4.9	4.5	4.5	-
Air System Fuel Efficiency (Pass-Mi/Gal)	16.1	18.5	25.4	26.6	26.6	26.6	1.4%
(Seat-Mi/Gal)	31.1	36.1	45.5	46.3	46.2	45.9	0.9%
Air System Load Factor (%)	51.6[5]	51.2	55.7	57.3	57.7	58.0	0.5%
Activity (Flights/Day)	12456[5]	6615	7328	8240	8959	11103	1.9%
Stage Length (St. Mi./Flight)	443[5]	639	660	677	712	745	0.5%
Aircraft Capacity (Seats/Flight)	121[5]	136	172	192	209	249	2.3%
Fleet Size TOTAL	1853[7]	1372	1549	1771	1992	2557	2.3%
4E WB	60	65	113	227	353	840	
3E WB	98	100	240	340	455	651	
4E NB	401	356	55	0	0	0	
3E NB	627	533	759	845	955	956	
2E NB	490	305	378	360	228	110	
TURBOPROP	177	13	4	0	0	0	

* Superscripts refer to sources in List of References

of air O-D round-trip passengers are included in the sample, the sample has only 32 percent of O-D demand by all modes. Similar figures for O-D passenger-miles are 64 percent for air and 45 percent for all modes. In terms of enplanements, which includes the effect of indirect trips (i.e., involving connections) from other city-pairs impacting on the 600 routes, the sample accounts for 83 percent of air passengers and 86 percent of air passenger-miles.

In interpreting the statistics in Table VI it is instructive to consider the average growth rates of various measures in the period from 1973 to 2000, as given in the last column. For example, note that while population grows at an average rate of only 1 percent/yr (an input based on Bureau of Census projections), O-D passenger demand (in pass -mi) grows at 4.1 percent/yr for all modes and that the air share grows from 61.9 percent to 80.6 percent of O-D demand during this period. In addition, air enplanements grow at more than five times the rate of population growth, although they are forecast to grow at a declining rate over the 27-year period. A driving force behind this demand growth is the projected rise in average income (Bureau of Economic Analysis, U.S. Commerce Department data), which results in increasing travel propensity. Furthermore, reductions in "real" air fares due to increasing load factor, the increase in the fraction of passengers carried nonstop, higher seating densities, and changeover of the fleet to larger, more economical aircraft, are an additional stimulus to air demand growth. Balanced against these demand-inducing effects is the rise in nominal fuel price from 12.56 ¢/gal in 1973 to 30¢/gal in the forecast years. The difference between the 1980 load factor of 55.6 percent and the target of 58 percent is due to the need to preserve frequency on low-frequency routes. (See preceeding discussion of fleet assignment model.) Since many low-frequency routes operated at load factors well below 58 percent in 1973, considerable time is required for demand to catch up with capacity. Also, retirements of DC-8 and B-707 aircraft on long-haul, low-density routes result in assignments of equal numbers of flights by DC-10/L-1011 aircraft (the smallest in-production aircraft with the necessary range) as replacements. Since demand growth cannot match this doubling of capacity, low load factors result. (The overall 1980 load factor for the DC-10/L-1011 aircraft is only 52 percent.) The emphasis on increasing frequency on low-density routes (which tend to be longer distance), while holding frequency growth down on high-density routes, plus the addition of 31 new routes mostly in the 800-to-2000 st mi bracket, results in a 106-st mi increase in average stage length. Frequency growth restraints on high-density routes also result in a nine-fold increase in the wide-body fleet, compared to a doubling of the total fleet. As expected, the smallest aircraft (2 ENB) showed the largest decline in fleet size.

Despite a near doubling of daily flights over the forecast period, assumed increases in airport capacities (as provided by UAL) generally prevent saturation. Two notable exceptions are at National and LaGuardia airports, where severe airside congestion is indicated by 1990. The situation at these two airports is aggravated by their inability to handle the B-747. A special provision in the aircraft assignment algorithm prevents assignment of the B-747 to short-haul routes (under 800 miles) involving New York or Washington. However, sufficient capacity probably exists at Dulles and Newark airports to relieve this congestion, provided airport usage patterns can be changed.

A large gain in air system fuel efficiency is indicated in Table VI, although almost all of the improvement occurs during the 1973-to-1980 period. Three effects combine to produce this large improvement, as indicated in Fig. 11*: (1) load factor contributes 8.8 percent of the increase, and is a direct consequence of the study assumption that the target load factor in all forecast years shall be 58 percent; (2) seating density contributes 11.4 percent of the increase, and is also a consequence of a study assumption, namely that the future trend is toward a 10/90 split between first class and tourist accommodations with slightly closer seat pitch on narrow-body aircraft and more seats across on wide-bodies; and (3) fleet mix contributes 13.1 percent of the increase. Of the three effects, only the last, which is achieved by the replacement of 4ENB aircraft by wide bodies, does not directly stem from a study assumption; it occurs because the demand and passenger/fleet assignment models predict this particular changeover in the fleet.

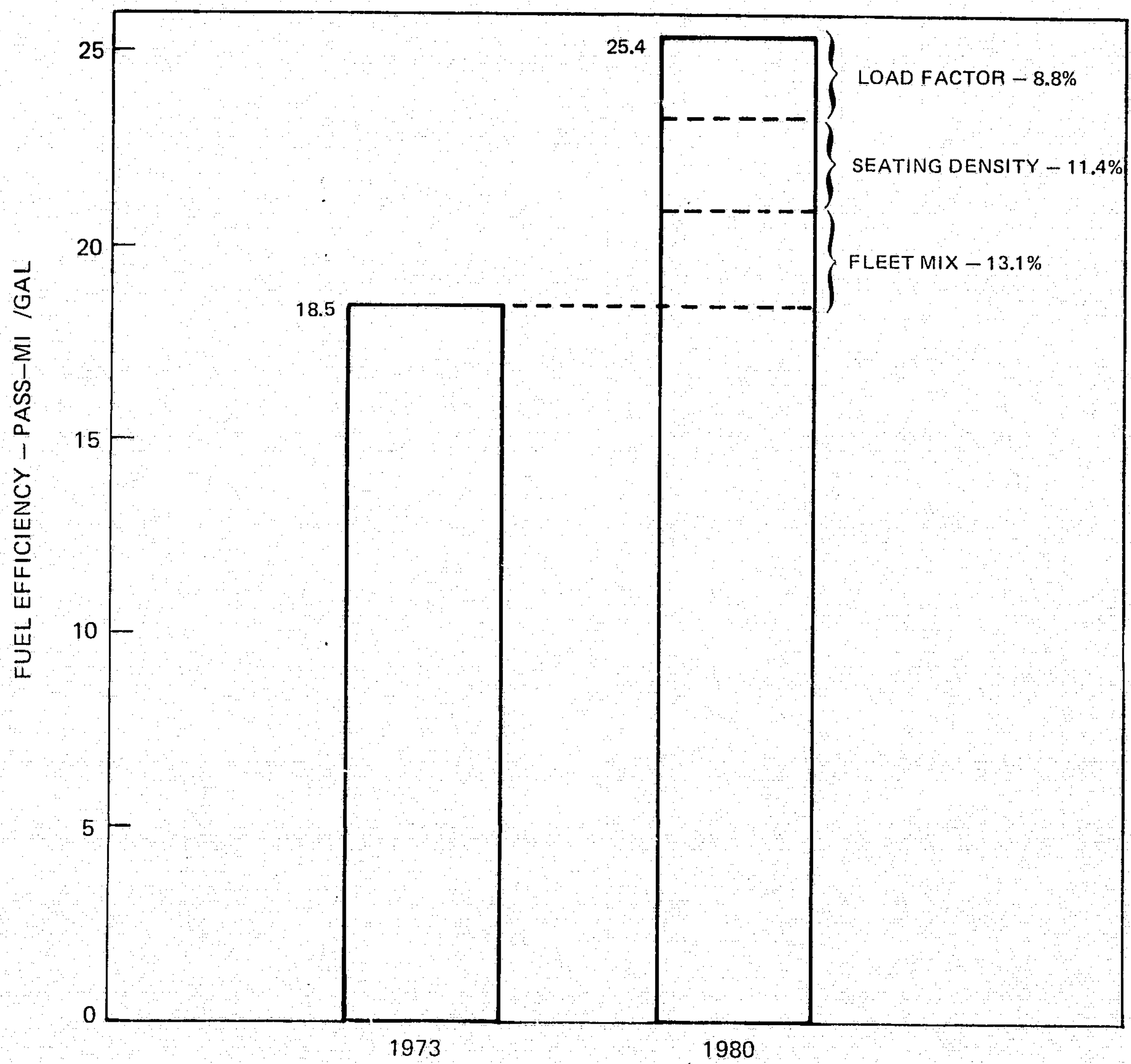
As shown in Fig. 14, the fleet mix is the largest single cause of improved fuel efficiency. During the 1973-to-1980 period, the percentage of wide-body aircraft in the fleet increases from 12 to 23 percent (Fig. 15). Despite the fact that the percentage of wide bodies continues to increase, fleet fuel efficiency gains level off beyond 1980 because these aircraft are being utilized at shorter stage lengths where their fuel efficiency is not much better than narrow bodies, and also because further increases in load factor are small and there are no further increases in seating density. That wide-body fuel use increases faster on short-distance routes as time progresses is illustrated graphically in Fig. 16. Nevertheless, the fact that these aircraft are both larger and more fuel-efficient results in slower growth rates in activity, fuel use, and fleet size than in enplaned pass-mi.

The steady increase in number of wide bodies is further reflected by the slow increase in airport activity (flights/day) compared with the much more rapid increase in passenger traffic. Also note that aircraft capacity

*Note that the improvements shown in Fig. 11 are multiplicative rather than additive; i.e., 25.4 = 1.131 x 1.114 x 1.088 x 18.5.

FIG. 14

1973–1980 FUEL EFFICIENCY IMPROVEMENT (PASS–MI/GAL)



76–03–71–9

BASELINE FLEET COMPOSITION

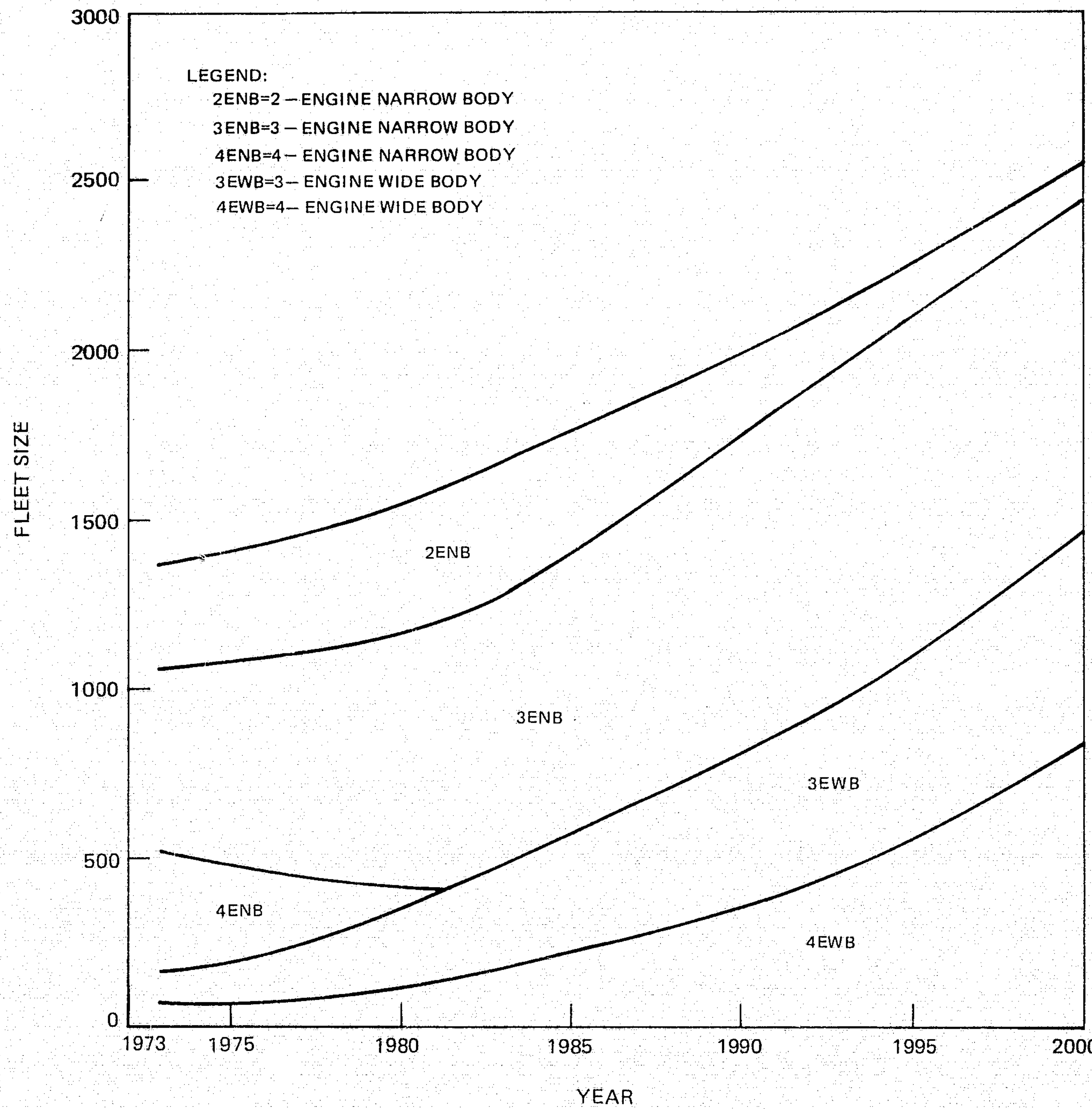
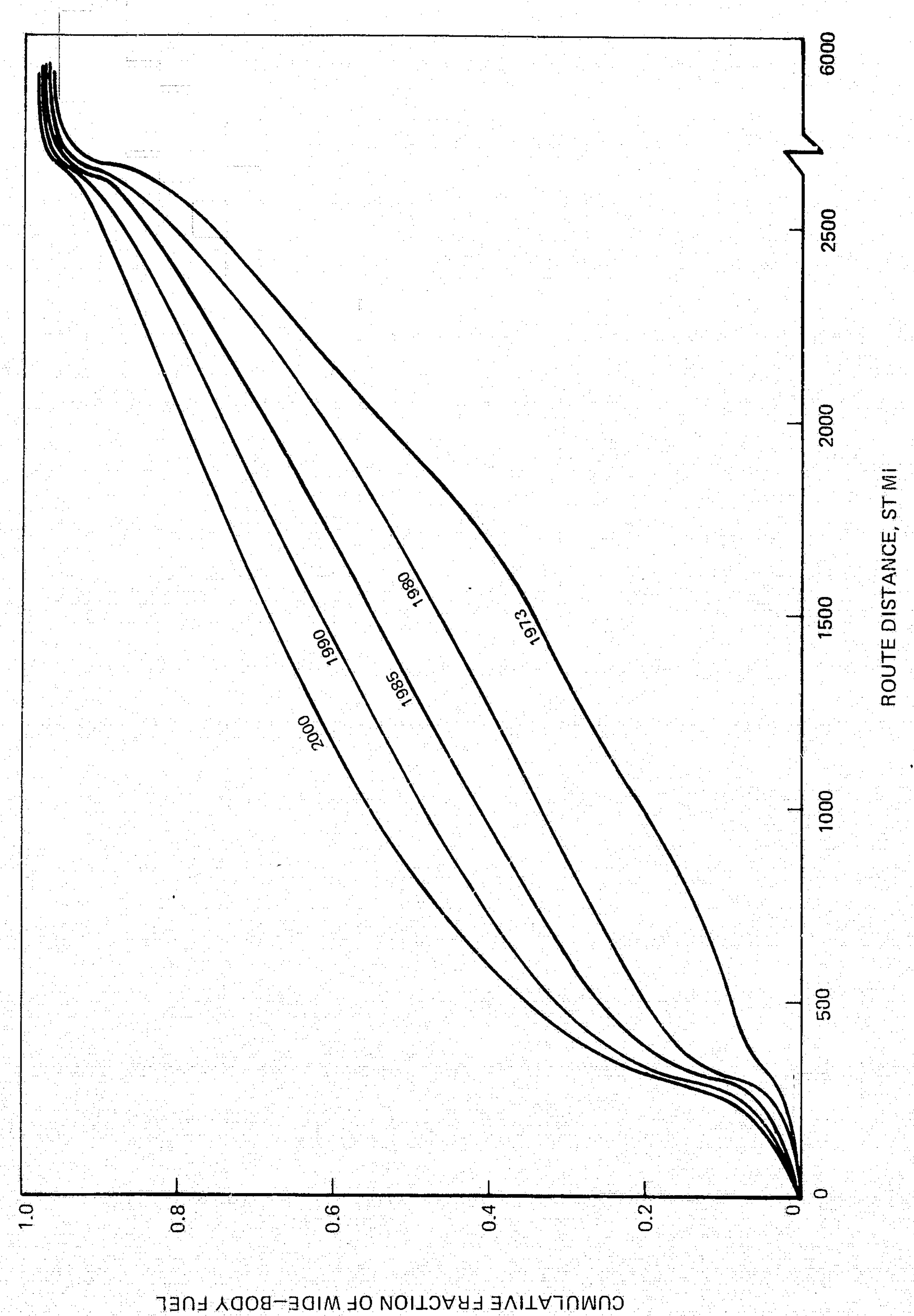


FIG. 16

WIDE–BODY FUEL USAGE WITH ROUTE DISTANCE

BASELINE CASE

3 EWB AND 4 EWB AIRCRAFT



76–03–71–7

grows at the same rate as total fleet size, almost doubling by the year 2000. This capacity growth is somewhat slower than the preceding period of equivalent years (1946 to 1973), during which even higher air demand growth was experienced.

Additional information on the way the baseline aircraft contribute to the fuel consumption (gal/yr), productivity (pass -mi/yr), and fuel efficiency (pass -mi/gal) of the system is presented in Tables VII to X for the forecast years 1980 to 2000, respectively. These tabulations also include load factor for each of 29 distance categories. It is apparent that, in each table, fuel efficiency increases with increasing stage length to about 1500 miles and then fluctuates widely in response to load factor variations.

Baseline Sensitivity Studies

Before proceeding on to the fuel-conservation options, it is instructive to consider the sensitivity of baseline results to fuel price and availability. The nominal fuel price of 30¢/gal in the forecast years is compatible with a petroleum cost of about $12/barrel in 1973 dollars. Depending on the availability of fuel in the future, there is a strong possibility that prices may rise above this level. The fuel price effect was estimated by running a case in which the airline fuel price was doubled; i.e., a price of 60¢/gal was used instead of the nominal 30¢/gal. Fuel allocations were simulated by restricting the total fuel available in each forecast year, thus forcing load factors up in order to satisfy demand.

Higher Fuel Price

Since an airline fuel cost of 60¢/gal represents a 30¢/gal increment from the baseline, auto operating costs and bus fares were increased to reflect similar 30¢/gal increases in gasoline and diesel fuel prices. Rail fares, which already include substantial subsidies, were not changed. In the first run of this scenario, the higher fuel price raised operating costs, thereby requiring higher fares and causing a decrease in demand. These effects were qualitatively correct but they were magnified by strict adherence to the frequency rules in Fig. 9. Because minimum frequencies on each route were set at 1973 values for those routes with less than 8 nonstop flights/day in each direction during the previous year and slightly lower than the previous-year frequency on higher-frequency routes, the reduced demand forced a reduction in load factors which further raised costs and fares, and further decreased demand. Although this effect was confined primarily to the 1980 forecast, the results obtained were felt to be unduly dictated by adherence to the 1973 frequencies. Therefore, the run was repeated with a relaxed

TABLE VII

1980 Baseline Run – 600 City Pair Sample

	FUEL – (000000)GALS/YR								PASSMILES – (000000)/YR									
DISTANCE	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRAC.	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRAC	LOAD FACTOR	PASS-MI/GAL
0- 100	0.	6.	1.	7.	7.	1.	22.	.003	0.	37.	2.	35.	59.	7.	139.	.001	.461	6.3
100- 200	4.	46.	12.	122.	78.	2.	264.	.040	21.	557.	79.	1403.	1148.	29.	3237.	.019	.587	12.3
200- 300	76.	81.	17.	211.	150.	1.	536.	.081	975.	1430.	180.	3328.	2677.	18.	8607.	.051	.597	16.1
300- 400	210.	30.	12.	213.	146.	0.	611.	.092	3530.	699.	169.	4121.	3066.	0.	11584.	.069	.598	19.0
400- 500	28.	64.	16.	227.	86.	0.	422.	.064	550.	1614.	291.	4970.	1873.	0.	9299.	.055	.597	22.0
500- 600	27.	39.	9.	185.	109.	0.	369.	.056	632.	1110.	161.	4486.	2484.	0.	8873.	.053	.594	24.0
600- 700	28.	70.	10.	130.	67.	0.	304.	.046	702.	1993.	199.	3173.	1495.	0.	7562.	.045	.573	24.9
700- 800	30.	39.	25.	164.	56.	0.	314.	.047	821.	1303.	567.	4202.	1267.	0.	8160.	.049	.600	26.0
800- 900	13.	43.	7.	179.	42.	0.	284.	.043	382.	1508.	168.	4780.	945.	0.	7783.	.046	.600	27.4
900-1000	14.	82.	6.	221.	59.	0.	381.	.057	442.	2772.	155.	5971.	1332.	0.	10672.	.064	.587	28.0
1000-1100	52.	45.	9.	160.	57.	0.	324.	.049	1582.	1568.	211.	4091.	1218.	0.	8670.	.052	.558	26.8
1100-1200	51.	77.	13.	183.	42.	0.	367.	.055	1582.	2732.	324.	4728.	695.	0.	10260.	.061	.556	28.0
1200-1300	9.	41.	6.	134.	0.	0.	191.	.029	278.	1487.	190.	3572.	0.	0.	5526.	.033	.563	28.9
1300-1400	0.	29.	7.	103.	0.	0.	140.	.021	0.	1021.	175.	2750.	0.	0.	3946.	.023	.551	28.2
1400-1500	10.	37.	12.	110.	0.	0.	169.	.025	321.	1364.	288.	2967.	0.	0.	4940.	.029	.560	29.2
1500-1600	26.	48.	5.	123.	0.	0.	202.	.030	783.	1680.	118.	3338.	0.	0.	5919.	.035	.541	29.3
1600-1700	6.	9.	6.	61.	0.	0.	81.	.012	206.	315.	144.	1642.	0.	0.	2306.	.014	.554	28.5
1700-1800	63.	79.	18.	132.	0.	0.	292.	.044	2090.	2899.	470.	3555.	0.	0.	9014.	.054	.557	30.9
1800-1900	8.	75.	19.	5.	0.	0.	106.	.016	263.	2686.	477.	113.	0.	0.	3539.	.021	.549	33.4
1900-2000	27.	62.	11.	8.	0.	0.	108.	.016	799.	1973.	256.	173.	0.	0.	3200.	.019	.490	29.6
2000-2100	5.	45.	5.	0.	0.	0.	55.	.008	116.	1204.	87.	0.	0.	0.	1407.	.008	.405	25.6
2100-2200	5.	59.	6.	2.	0.	0.	71.	.011	168.	1845.	130.	39.	0.	0.	2183.	.013	.488	30.7
2200-2300	19.	58.	10.	0.	0.	0.	87.	.013	523.	1677.	190.	0.	0.	0.	2391.	.014	.447	27.5
2300-2400	11.	69.	10.	0.	0.	0.	90.	.014	373.	1772.	156.	0.	0.	0.	2301.	.014	.412	25.6
2400-2500	148.	129.	17.	0.	0.	0.	295.	.044	4986.	4290.	413.	0.	0.	0.	9689.	.058	.537	32.8
2500-2600	60.	86.	20.	0.	0.	0.	166.	.025	1894.	2403.	400.	0.	0.	0.	4697.	.028	.465	28.3
2600-2700	188.	36.	12.	0.	0.	0.	237.	.036	6844.	1203.	320.	0.	0.	0.	8367.	.050	.591	35.3
2700-2800	24.	29.	9.	0.	0.	0.	62.	.009	705.	883.	184.	0.	0.	0.	1771.	.011	.472	28.6
2800-6000	79.	4.	4.	0.	0.	0.	88.	.013	1766.	114.	96.	0.	0.	0.	1976.	.012	.393	22.5
TOTALS	1221.	1519.	315.	2682.	898.	3.	6638.		33335.	46138.	6601.	63436.	18460.	54.	168023.		.556	25.3
PERCENT	.184	.229	.047	.404	.135	.001			.198	.275	.039	.378	.110	.000				

TABLE VIII

1985 Baseline Run – 600 City Pair Sample

DISTANCE	FUEL – (000000)GALS/YR 4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRACTION	PASSMILES – (000000)/YR 4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRAC.	LOAD FACTOR	PASS-MI/ GAL
0- 100	0.	8.	0.	5.	9.	0.	22.	.003	0.	60.	0.	32.	89.	0.	180.	.001	.585	8.2
100- 200	46.	116.	0.	117.	67.	0.	347.	.041	286.	1571.	0.	1418.	1021.	0.	4296.	.019	.597	12.4
200- 300	203.	157.	0.	246.	120.	0.	726.	.086	2597.	2781.	0.	4068.	2184.	0.	11630.	.052	.600	16.0
300- 400	390.	55.	0.	241.	130.	0.	816.	.097	6529.	1281.	0.	4780.	2818.	0.	15408.	.069	.601	18.9
400- 500	129.	90.	0.	255.	72.	0.	547.	.065	2556.	2358.	0.	5827.	1609.	0.	12350.	.056	.601	22.6
500- 600	73.	70.	0.	229.	101.	0.	473.	.056	1739.	2118.	0.	5682.	2339.	0.	11873.	.053	.600	25.1
600- 700	71.	70.	0.	173.	59.	0.	374.	.044	1848.	2283.	0.	4545.	1363.	0.	10039.	.045	.607	26.8
700- 800	57.	107.	0.	153.	57.	0.	374.	.045	1585.	3661.	0.	4131.	1295.	0.	10673.	.048	.608	28.5
800- 900	71.	46.	0.	201.	55.	0.	373.	.044	2097.	1630.	0.	5498.	1258.	0.	10482.	.047	.600	28.1
900-1000	46.	114.	0.	252.	67.	0.	479.	.057	1460.	4138.	0.	7057.	1525.	0.	14181.	.064	.600	29.6
1000-1100	99.	70.	0.	179.	67.	0.	415.	.049	3003.	2417.	0.	4744.	1437.	0.	11601.	.052	.559	28.0
1100-1200	109.	108.	0.	189.	82.	0.	488.	.058	3362.	3825.	0.	5085.	1767.	0.	14039.	.063	.560	28.8
1200-1300	28.	67.	0.	154.	0.	0.	250.	.030	889.	2434.	0.	4215.	0.	0.	7538.	.034	.562	30.2
1300-1400	15.	45.	0.	112.	0.	0.	173.	.021	494.	1649.	0.	3088.	0.	0.	5231.	.024	.560	30.2
1400-1500	42.	43.	0.	128.	0.	0.	213.	.025	1407.	1564.	0.	3576.	0.	0.	6548.	.029	.564	30.7
1500-1600	67.	51.	0.	140.	0.	0.	258.	.031	2257.	1929.	0.	3893.	0.	0.	8080.	.036	.567	31.3
1600-1700	19.	14.	0.	70.	0.	0.	103.	.012	656.	534.	0.	1977.	0.	0.	3167.	.014	.571	30.7
1700-1800	126.	90.	0.	152.	0.	0.	369.	.044	4429.	3390.	0.	4233.	0.	0.	12052.	.054	.574	32.7
1800-1900	49.	81.	0.	0.	0.	0.	130.	.015	1632.	2887.	0.	0.	0.	0.	4518.	.020	.549	34.8
1900-2000	27.	91.	0.	0.	0.	0.	117.	.014	895.	3144.	0.	0.	0.	0.	4039.	.018	.536	34.5
2000-2100	5.	51.	0.	0.	0.	0.	56.	.007	139.	1640.	0.	0.	0.	0.	1779.	.008	.487	31.8
2100-2200	5.	79.	0.	0.	0.	0.	84.	.010	175.	2578.	0.	0.	0.	0.	2753.	.012	.506	32.8
2200-2300	19.	74.	0.	0.	0.	0.	93.	.011	610.	2499.	0.	0.	0.	0.	3108.	.014	.519	33.4
2300-2400	21.	80.	0.	0.	0.	0.	102.	.012	706.	2268.	0.	0.	0.	0.	2974.	.013	.456	29.2
2400-2500	216.	142.	0.	0.	0.	0.	358.	.043	7157.	4573.	0.	0.	0.	0.	11730.	.053	.529	32.8
2500-2600	84.	101.	0.	0.	0.	0.	186.	.022	2840.	3055.	0.	0.	0.	0.	5894.	.027	.507	31.7
2600-2700	256.	44.	0.	0.	0.	0.	301.	.036	9234.	1115.	0.	0.	0.	0.	10349.	.047	.568	34.4
2700-2800	24.	45.	0.	0.	0.	0.	69.	.008	768.	1511.	0.	0.	0.	0.	2280.	.010	.526	33.0
2800-6000	108.	4.	0.	0.	0.	0.	112.	.013	3193.	0.	0.	0.	0.	0.	3193.	.014	.491	28.5
TOTALS	2406.	2117.	0.	2997.	888.	0.	8408.		64538.	64894.	0.	73850.	18704.	0.	221987.		.570	26.4
PERCENT	.286	.252	.000	.356	.106	.000			.291	.292	.000	.333	.084	.000				

TABLE IX

1990 Baseline Run - 600 City Fair Sample

	FUEL - (000000)GALS/YR								PASSMILES - (000000)/YR									
DISTANCE	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRACTION	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRAC	LOAD FACTOR	PASS-MI/GAL
0- 100	0.	14.	0.	13.	3.	0.	30.	.003	0.	95.	0.	95.	31.	0.	221.	.001	.576	7.4
100- 200	102.	214.	0.	121.	26.	0.	462.	.044	665.	2877.	0.	1455.	366.	0.	5363.	.019	.584	11.6
200- 300	327.	292.	0.	265.	50.	0.	933.	.089	4144.	5196.	0.	4385.	885.	0.	14609.	.052	.599	15.7
300- 400	552.	166.	0.	259.	47.	0.	1025.	.098	9204.	3810.	0.	5144.	988.	0.	19146.	.069	.598	18.7
400- 500	200.	164.	0.	284.	30.	0.	677.	.065	3918.	4327.	0.	6497.	638.	0.	15380.	.055	.601	22.7
500- 600	70.	186.	0.	265.	55.	0.	577.	.055	1666.	5512.	0.	6546.	1219.	0.	14943.	.054	.594	25.9
600- 700	129.	90.	0.	198.	40.	0.	457.	.043	3376.	2843.	0.	5069.	895.	0.	12183.	.044	.598	26.7
700- 800	81.	149.	0.	175.	48.	0.	453.	.043	2259.	4974.	0.	4651.	1079.	0.	12963.	.046	.601	28.6
800- 900	126.	49.	0.	223.	63.	0.	461.	.044	3736.	1709.	0.	6107.	1423.	0.	12975.	.046	.600	28.1
900-1000	130.	102.	0.	297.	82.	0.	611.	.058	4069.	3731.	0.	8340.	1861.	0.	18000.	.064	.601	29.5
1000-1100	164.	65.	0.	221.	76.	0.	527.	.050	4987.	2249.	0.	5879.	1635.	0.	14749.	.053	.559	28.0
1100-1200	181.	105.	0.	218.	109.	0.	613.	.058	5601.	3716.	0.	5888.	2334.	0.	17539.	.063	.560	28.6
1200-1300	55.	79.	0.	190.	0.	0.	325.	.031	1736.	2839.	0.	5186.	0.	0.	9760.	.035	.560	30.0
1300-1400	51.	40.	0.	123.	0.	0.	214.	.020	1671.	1477.	0.	3381.	0.	0.	6529.	.023	.564	30.5
1400-1500	79.	28.	0.	157.	0.	0.	264.	.025	2608.	1013.	0.	4354.	0.	0.	7975.	.029	.560	30.2
1500-1600	119.	57.	0.	157.	0.	0.	333.	.032	3938.	2088.	0.	4324.	0.	0.	10350.	.037	.558	31.1
1600-1700	33.	9.	0.	99.	0.	0.	141.	.013	1081.	347.	0.	2756.	0.	0.	4185.	.015	.562	29.7
1700-1800	194.	90.	0.	175.	0.	0.	458.	.044	6498.	3294.	0.	4829.	0.	0.	14621.	.052	.560	31.9
1800-1900	99.	62.	0.	0.	0.	0.	161.	.015	3318.	2225.	0.	0.	0.	0.	5543.	.020	.555	34.4
1900-2000	67.	79.	0.	0.	0.	0.	145.	.014	2271.	2867.	0.	0.	0.	0.	5137.	.018	.560	35.4
2000-2100	3.	56.	0.	0.	0.	0.	59.	.006	109.	2047.	0.	0.	0.	0.	2157.	.008	.558	36.6
2100-2200	3.	100.	0.	0.	0.	0.	103.	.010	115.	3657.	0.	0.	0.	0.	3773.	.014	.562	36.0
2200-2300	42.	67.	0.	0.	0.	0.	110.	.010	1425.	2445.	0.	0.	0.	0.	3870.	.014	.559	35.2
2300-2400	44.	76.	0.	0.	0.	0.	119.	.011	1288.	2401.	0.	0.	0.	0.	3689.	.013	.489	31.0
2400-2500	300.	134.	0.	0.	0.	0.	434.	.041	10413.	4863.	0.	0.	0.	0.	15276.	.055	.573	35.2
2500-2600	113.	101.	0.	0.	0.	0.	214.	.020	3781.	3278.	0.	0.	0.	0.	7060.	.025	.530	33.0
2600-2700	322.	61.	0.	0.	0.	0.	383.	.036	11569.	2297.	0.	0.	0.	0.	13866.	.050	.597	36.2
2700-2800	17.	59.	0.	0.	0.	0.	76.	.007	575.	2233.	0.	0.	0.	0.	2809.	.010	.581	37.0
2800-6000	129.	5.	0.	0.	0.	0.	135.	.013	4255.	199.	0.	0.	0.	0.	4454.	.016	.571	33.0
TOTALS	3732.	2699.	0.	3440.	628.	0.	10498.		100276.	80611.	0.	84886.	13352.	0.	279124.		.578	26.6
PERCENT	.356	.257	.000	.328	.060	.000			.359	.289	.000	.304	.048	.000				

TABLE X

2000 Baseline Run - 600 City Pair Sample

	FUEL - (000000)GALS/YR								PASSMILES - (000000)/YR								LOAD	PASS-MI
DISTANCE	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRACTION	4EWB	3EWB	4ENB	3ENB	2ENB	TBPRP	TOTAL	FRAC.	FACTOR	GAL
0- 100	22.	24.	0.	6.	1.	0.	53.	.003	96.	190.	0.	42.	12.	0.	339.	.001	.597	6.4
100- 200	419.	309.	0.	68.	10.	0.	807.	.049	3256.	4365.	0.	853.	147.	0.	8621.	.020	.600	10.7
200- 300	941.	474.	0.	171.	21.	0.	1607.	.098	11846.	8656.	0.	2848.	370.	0.	23720.	.055	.600	14.8
300- 400	1108.	303.	0.	193.	16.	0.	1620.	.099	18488.	7040.	0.	3852.	326.	0.	29706.	.069	.600	18.3
400- 500	541.	274.	0.	241.	12.	0.	1068.	.065	10735.	7289.	0.	5528.	258.	0.	23810.	.055	.600	22.3
500- 600	314.	317.	0.	227.	23.	0.	881.	.054	7526.	9489.	0.	5608.	505.	0.	23129.	.053	.599	26.3
600- 700	351.	133.	0.	198.	17.	0.	699.	.043	9161.	4188.	0.	5101.	381.	0.	18830.	.043	.600	26.9
700- 800	137.	325.	0.	153.	25.	0.	640.	.039	3816.	10854.	0.	4068.	552.	0.	19290.	.045	.600	30.1
800- 900	268.	114.	0.	264.	35.	0.	680.	.042	7927.	3968.	0.	7203.	784.	0.	19882.	.046	.598	29.2
900-1000	352.	210.	0.	294.	41.	0.	897.	.055	11045.	7570.	0.	8233.	933.	0.	27781.	.064	.598	31.0
1000-1100	346.	88.	0.	317.	49.	0.	801.	.049	10518.	3085.	0.	8451.	1003.	0.	23056.	.053	.560	28.8
1100-1200	413.	129.	0.	318.	55.	0.	914.	.056	12811.	4547.	0.	8516.	1162.	0.	27036.	.062	.559	29.6
1200-1300	194.	62.	0.	276.	0.	0.	532.	.033	6149.	2227.	0.	7529.	0.	0.	15905.	.037	.561	29.9
1300-1400	145.	22.	0.	186.	0.	0.	353.	.022	4723.	802.	0.	4925.	0.	0.	10450.	.024	.551	29.6
1400-1500	158.	84.	0.	145.	0.	0.	387.	.024	5187.	3060.	0.	4033.	0.	0.	12280.	.028	.560	31.7
1500-1600	253.	80.	0.	171.	0.	0.	505.	.031	8403.	2929.	0.	4729.	0.	0.	16061.	.037	.559	31.8
1600-1700	59.	28.	0.	123.	0.	0.	211.	.013	1980.	1033.	0.	3422.	0.	0.	6435.	.015	.560	30.5
1700-1800	399.	49.	0.	250.	0.	0.	699.	.043	13366.	1799.	0.	6829.	0.	0.	21994.	.051	.557	31.5
1800-1900	187.	56.	0.	0.	0.	0.	244.	.015	6299.	2061.	0.	0.	0.	0.	8360.	.019	.560	34.3
1900-2000	170.	68.	0.	0.	0.	0.	239.	.015	5745.	2496.	0.	0.	0.	0.	8241.	.019	.559	34.5
2000-2100	60.	31.	0.	0.	0.	0.	91.	.006	2033.	1123.	0.	0.	0.	0.	3156.	.007	.560	34.7
2100-2200	117.	59.	0.	0.	0.	0.	177.	.011	3947.	2165.	0.	0.	0.	0.	6112.	.014	.559	34.5
2200-2300	133.	47.	0.	0.	0.	0.	180.	.011	4453.	1719.	0.	0.	0.	0.	6172.	.014	.559	34.3
2300-2400	102.	69.	0.	0.	0.	0.	172.	.010	3433.	2490.	0.	0.	0.	0.	5924.	.014	.556	34.4
2400-2500	582.	90.	0.	0.	0.	0.	672.	.041	20170.	3286.	0.	0.	0.	0.	23455.	.054	.576	34.9
2500-2600	216.	84.	0.	0.	0.	0.	300.	.018	7243.	3047.	0.	0.	0.	0.	10289.	.024	.560	34.3
2600-2700	554.	49.	0.	0.	0.	0.	603.	.037	19839.	1874.	0.	0.	0.	0.	21713.	.050	.597	36.0
2700-2800	90.	32.	0.	0.	0.	0.	122.	.007	3134.	1223.	0.	0.	0.	0.	4357.	.010	.583	35.7
2800-6000	196.	9.	0.	0.	0.	0.	205.	.013	6758.	331.	0.	0.	0.	0.	7090.	.016	.597	34.6
TOTALS	8829.	3621.	0.	3601.	305.	0.	16356.		230087.	104906.	0.	91768.	6433.	0.	433194.		.580	26.5
PERCENT	.540	.221	.000	.220	.019	.000			.531	.242	.000	.212	.015	.000				

rule for minimum frequency ($F_{MIN} = 3/4\ F_0$ on all routes.) In all other respects, the assumptions and inputs for the 60¢/gal fuel case were identical to the baseline. The final results are given in Table XI, which also includes the baseline results for comparative purposes.

The basic effect of doubling the fuel price is to increase airplane operating costs, thus requiring generally higher fares. Whereas fares decreased with time in the baseline case, the higher cost of fuel results in considerably higher fares in 1980 (15 percent more than the baseline fare), and although fares decrease from the 1980 level in succeeding years, they remain high relative to 1973.

A direct result of higher fares is a slower growth in demand (including travel propensity), personal travel growth being affected more than business travel because of its greater sensitivity to price. Similarly, fuel consumed, activity, and fleet size grow more slowly because of the lower passenger demand.

Note, however, that the greatest discrepancies between the baseline and 60¢/gal fuel cases occur in 1980; in each succeeding forecast year the effect of the fuel price increase diminishes. Several factors contribute to produce this result, although the simplest explanation is that the perceived disutility of air travel is decreasing because average income continues to rise and because operating costs improve as the fleet mix evolves toward wide bodies (note, however, that forecasts of real income compatible with the economic impact of sharply higher petroleum prices were not available for use in this scenario).

Finally, note that the percentage of wide-body aircraft in the fleet for the 60¢/gal fuel case lags behind the baseline case by from 1 percent in 1980 to 2 percent in 2000 because of the lower demand. Nevertheless, fuel efficiency is somewhat better because wide-body usage on short routes diminishes relative to the baseline.

Fuel Allocation

To simulate the effect of a fuel-allocation environment, the following changes were made in baseline case assumptions:

1. Higher load factors than the baseline value of 58 percent were allowed in order to conserve fuel.

2. The minimum frequency, F_{MIN}, was reduced from $(2 + 0.75\ F_0)$ on high-frequency routes and $(1 + 0.875\ F_0)$ on low-frequency routes

TABLE XI

BASELINE AND 60¢/GALLON SCENARIOS
(RECAT 600 City-Pair Network)

	1973	1980		1985		1990		2000		Average Growth Rate: 1973-2000	
Total Population - 247 SMSA's (10^6 Persons)	149.6	161.3		170.5		180.5		196.3		1.0%	
Average Income - 247 SMSA's (1973 $/Person/Yr)	5242	6552		7426		8382		11,003		2.8%	
Aircraft Fuel Price (1973 $/Gal)	0.1256	0.30	0.60	0.30	0.60	0.30	0.60	0.30	0.60	0.30	0.60
Travel Propensity - (Intercity Trips/Person/Yr)	2.60	3.11	2.82	3.52	3.20	3.88	3.53	4.86	4.44	2.3%	2.0%
O-D Passenger Demand - All Modes (10^6 Round Trips/Yr)	139.6	182.7	166.8	221.5	202.4	260.4	238.3	358.3	329.6	3.6%	3.2%
(10^9 Pass-Mi/Yr)	119.2	164.7	147.7	204.3	183.1	245.4	220.2	352.6	317.6	4.1%	3.7%
Air Share of Total O-D Demand (% of Round Trips)	30.4	36.1	33.7	39.7	37.2	42.3	39.8	48.1	45.6	1.7%	1.5%
(% of Pass-Miles)	61.9	69.4	66.7	73.1	70.5	75.7	73.2	80.6	78.5	1.0%	0.9%
Enplaned Air Passengers (10^6 One-Way Pass/Yr)	147.4	228.4	195.7	303.6	260.8	379.7	327.5	593.7	519.2	5.3%	4.8%
(10^9 Pass-Mi/Yr)	107.5	168.8	143.4	224.1	191.2	280.5	240.8	436.1	379.2	5.3%	4.8%
Average Growth Rate of Pass-Mi - O-D - All Modes(%/Yr)	-	4.7	3.1	4.4	4.4	3.7	3.8	3.7	3.7		
- O-D - Air (%/Yr)	-	6.5	4.2	5.5	5.6	4.5	4.5	4.3	4.5		
- Enplaned - Air (%/Yr)	-	6.7	4.2	5.8	5.9	4.6	4.7	4.5	4.6		
Business Fraction of O-D Pass - All Modes (%)	31.5	31.6	31.5	31.7	31.6	31.7	31.7	31.8	31.8	0	0
- Air (%)	57.9	53.0	54.6	50.6	52.1	48.7	50.2	45.4	46.6	-0.9%	-0.8%
O-D Pass Trip Length - All Modes (St. Mi.)	427	451	443	461	452	471	462	492	482	0.5%	0.4%
- Air (St. Mi.)	869	868	876	850	857	844	851	824	829	-0.2%	-0.2%
Routes with Nonstop Service	483	485	485	494	487	503	499	514	510	0.2%	0.2%
Air Pass. Carried Nonstop (%)	89.0	91.4	89.7	92.6	91.4	93.3	92.4	94.1	93.4	0.2%	0.2%
Fares Relative to 1973	1.000	0.995	1.147	0.957	1.110	0.950	1.106	0.937	1.094	-0.2%	0.3%
Fuel Consumed by Air (10^6 Gal/Yr)	5808	6656	5587	8440	7117	10536	8982	16400	14156	3.9%	3.4%
Average Growth Rate of Fuel Consumed by Air (%/Yr)	-	2.0	-0.6	4.9	5.0	4.5	4.8	4.5	4.7		
Air System Fuel Efficiency (Pass-Mi/Gal)	18.5	25.4	25.7	26.6	26.9	26.6	26.8	26.6	26.8	1.4%	1.4%
(Seat-Mi/Gal)	36.1	45.5	45.4	46.3	46.7	46.2	46.4	45.9	46.1	0.9%	0.9%
Air System Load Factor (%)	51.2	55.7	56.5	57.3	57.5	57.7	57.8	58.0	58.1	0.5%	0.5%
Activity (Flights/Day)	6615	7328	6409	8240	7320	8959	8134	11103	10160	1.9%	1.6%
Stage Length (St. Mi./Flight)	639	660	630	577	651	712	689	745	726	0.5%	0.5%
Aircraft Capacity (Seats/Flight)	136	172	172	192	191	209	204	249	242	2.3%	2.2%
Fleet Size: TOTAL	1372	1549	1319	1771	1538	1992	1771	2557	2300	2.3%	1.9%
4E WB	65	113	107	227	186	353	276	840	670		
3E WB	100	240	182	34.	291	455	394	651	609		
4E NB	356	55	55	0	0	0	0	0	0		
3E NB	533	759	615	845	698	955	848	956	889		
2E NB	305	378	357	360	364	228	253	110	132		
Turboprop	13	4	4	0	0	0	0	0	0		

to (0.75 F_O) on all routes, where F_O is the previous year's frequency. This means that a 25 percent frequency reduction is allowed on all routes, consistent with the necessity to increase load factor in a limited-fuel scenario.

3. Aircraft were ranked for assignment using fuel efficiency (seat-miles/gallon) as the basic criterion rather than 15 percent ROI load factor.

In the first fuel-allocation scenario, the maximum load factor was set at 70 percent, a level above which significant demand rejection would probably occur. As in the baseline case, fares were adjusted to maintain a 12 percent system-wide ROI. From Table XII, it can be seen that in 1980, the increased load factor caused an 18 percent fare reduction from the baseline case which stimulated a 21 percent increase in enplaned passenger-miles. As a result, only a 3.3 percent fuel saving relative to the baseline case was achieved, despite significantly higher aircraft fuel efficiency (pass-miles/gal).

Since demand stimulation through fare cuts runs counter to the necessity to limit fuel consumption in an allocation environment, the scenario was repeated with fares held at the baseline level. These results, also presented in Table XII, show a decrease of 8.5 percent in total fuel used from 1973 to 1980 and a saving of 20.1 percent in total 1980 fuel when compared with the baseline case. Although total flights are reduced substantially from the baseline, only a 2.4 percent decline in demand occurs. Most of the fuel savings result from the increase in load factor to 67 percent, a consequence of both the high maximum (target) load factor of 70 percent and the freedom to reduce frequencies on low-frequency, low-load factor routes. Some fuel savings are also due to a more fuel-efficient fleet, as indicated by the increase in seat-miles/gallon. Because of the combination of high load factor and fixed fares, the ROI is 19.2 percent.

Similar results are obtained for later forecast years, with substantial reductions in fuel, flights, and fleet size resulting from the high load factors; total fuel savings are about 25 percent in 1985, 1990, and 2000. As in 1980, demand is reduced by only about 2.5 percent, but fewer passengers are able to travel nonstop.

Since 70 percent may represent a practical upper limit on load factor, this scenario represents the minimum fuel usage attainable, given the other assumptions of the scenario. Two other scenarios were also postulated

TABLE XII

FUEL ALLOCATION SCENARIOS
(RECAT 600 City-Pair Network)

	1973	1980					1985			
		Baseline	70% LF_{MAX} 12% ROI	70% LF_{MAX} Base Fare	1973 Fuel	50% Base Fuel Incrs.	Baseline	1973 Fuel	70% LF_{MAX} Base Fare	50% Base Fuel Increase
Enplaned Air Pass-Mi (10^9)	107.5	168.9	204.9	164.9	165.6	165.9	224.1	215.2	216.0	217.2
Air Pass. Carried Nonstop (%)	89.0	91.4	90.5	89.2	89.6	89.8	92.6	89.4	89.6	90.1
Fares Relative to 1973	1.0	0.995	0.811	0.995*	0.995*	0.995*	0.957	0.957*	0.957*	0.957*
Return on Investment (%)	7.0	12.0*	12.0*	19.2	15.2	12.3	12.0*	22.6	19.0	14.7
Maximum Load Factor (%)	—	58.0*	70.0*	70.0*	62.6	57.8	58.0*	76.8	70.0*	62.5
Average Load Factor (%)	51.2	55.7	68.9	67.0	61.0	56.7	57.13	75.4	69.1	62.0
Total Fuel (10^9 Gals/Yr)	5.808	6.656	6.436	5.315	5.807*	6.225*	8.440	5.809*	6.404	7.104*
Increase from 1973	—	14.6%	10.8%	-8.5%	0	7.2%	45.3%	0	10.3%	22.3%
Savings Relative to Baseline	—	—	3.3%	20.1%	12.8%	6.5%	—	31.2%	24.1%	15.8%
Pass-Mi/Gal	18.5	25.4	31.8	31.0	28.5	26.7	26.6	37.1	33.7	30.6
Seat-Mi/Gal	36.1	45.5	46.2	46.3	46.7	47.0	46.3	49.2	48.8	49.3
Flights/Day	6615	7328	6965	6151	6449	6607	8240	6076	6361	6746
Fleet - Total	1372	1549	1449	1259	1327	1365	1771	1246	1315	1402
4E WB	65	113	111	73	82	102	227	86	123	139
3E WB	100	240	340	266	339	396	340	488	522	636
4E NB	356	55*	55*	55*	55*	55*	0*	0*	0*	0*
3E NB	533	759	550	493	486	464	845	322	326	297
2E NB	305	378	388	367	360	343	360	350	345	330
Turboprop	13	4*	4*	4*	4*	4*	0*	0*	0*	0*

* Value held approximately constant (fuel cannot be held exactly constant)

Notes: Baseline: $F_{MIN} = 2 + 3/4\ F_0$ ($F_0 > 8$)
$F_{MIN} = 1 + 7/8\ F_0$ ($F_0 < 8$)
Aircraft ranked by 15% ROI load factor

Others: $F_{MIN} = 3/4\ F_0$ (all F_0)
Aircraft ranked by fuel efficiency

TABLE XII (cont'd)

FUEL ALLOCATION SCENARIOS
(RECAT 600 City-Pair Network)

	1990				2000			AVG. GROWTH, 1973-2000		
	Baseline	1973 Fuel	70% LF_{MAX} Base Fare	50% Base Fuel Increase	Baseline	70% LF_{MAX} Base Fare	50% Base Fuel Growth	Baseline	70% LF_{MAX} Base Fare	50% Base Fuel Increase
Enplaned Air Pass-Mi (10^9)	280.5	267.5	270.5	271.7	436.1	425.0	422.7	5.3%	5.2%	5.2%
Air Pass. Carried Nonstop (%)	93.3	90.0	90.7	91.2	94.1	92.7	92.5			
Fares Relative to 1973	0.950	0.950*	0.950*	0.950*	0.937	0.937*	0.937*	-0.2%	-0.2%	-0.2%
Return on Investment (%)	12.0*	30.4	18.7	16.7	12.0*	18.3	22.6			
Maximum Load Factor (%)	58.0*	92.1	70.0*	66.6	58.0*	70.0*	78.0			
Average Load Factor (%)	57.7	91.2	69.7	66.3	58.0	69.8	77.9			
Total Fuel (10^9 Gals/Yr)	10.536	5.805*	7.791	8.161*	16.400	12.516	11.066*	3.9%	2.9%	2.4%
Increase from 1973	81.4%	0	34.1%	40.5%	182.4%	115.5%	90.5%			
Savings Relative to Baseline	—	44.9%	26.1%	22.5%	—	23.5%	32.5%			
Pass-Mi/Gal	26.6	46.1	34.7	33.3	26.6	34.0	38.2			
Seat-Mi/Gal	46.2	50.5	49.8	50.3	45.9	48.6	49.0			
Flights/Day	8959	5862	6438	6734	11103	8238	7719	1.9%	0.8%	0.6%
Fleet - Total	1992	1219	1389	1456	2557	1859	1718	2.3%	1.1%	0.8%
4E WB	353	40	169	158	840	466	357			
3E WB	455	632	799	883	651	1159	1087			
4E NB	0*	0*	0*	0*	0*	0*	0*			
3E NB	955	257	207	215	956	115	145			
2E NB	228	290	213	200	110	118	130			
Turboprop	0*	0*	0*	0*	0*	0*	0*			

* Value held approximately constant (Fuel cannot be held exactly constant)

Notes: Baseline: $F_{MIN} = 2 + 3/4\ F_0$ $(F_0 > 8)$
$F_{MIN} = 1 + 7/8\ F_0$ $(F_0 < 8)$
Aircraft ranked by 15% ROI load factor

Others: $F_{MIN} = 3/4\ F_0$ (all F_0)
Aircraft ranked by fuel efficiency

in which a fixed fuel allocation was met by varying the maximum load factor.* In one, the fuel usage was held at the 1973 level (zero rate of growth), while in the other fuel use was set half-way between the 1973 and baseline scenario levels (half the baseline increases). The zero-increase fuel scenario resulted in load factor exceeding 70 percent by 1985, while the 50 percent baseline fuel-increase scenario required excessive load factors in the year 2000. (No allowance was made for any demand rejection at these high load factors.) The results for these scenarios are similar, in varying degrees, to the results of the 70 percent load factor scenario: higher load factors; fewer flights; smaller fleets with increased emphasis on larger, more fuel-efficient aircraft; slightly lower demand, etc.

A summary of results for the fuel-allocation scenarios appears in Fig. 17 in a plot of total fuel consumed as a function of average load factor. This figure includes the three cases in Table XII for which fares were fixed at the baseline values. Thus it depicts the fuel conservation potential of increasing load factors above the baseline target level of 58 percent.

The symboled points are taken directly from Table XII; curves connecting the fuel allocation scenario points (dashed lines) and forecast years (solid lines) are shown to illustrate the probable continuity of the results. As noted before, even though a target load factor for the system is specified as an input item, the actual load factor achieved is generally somewhat less than this value, particularly in 1980, because of the minimum-frequency rule and the very low 1973 load factors on many routes.

Figure 17 is useful in that it shows the load factor required for a specified fuel allocation, assuming fuel used is not constrained by other means, such as tax levies on fuel or fare, which would depress demand. It is important to stress, however, that very high load factors, compared with historical practice, are depicted in Fig. 17. Since neither the effects of airline competition or the demand rejection that might occur in achieving high load factors have been simulated, the extreme right-hand portion of Fig. 17 is of only academic interest.

From the data shown in Table XII, the fuel allocation scenarios appear attractive. Fuel consumption and airport congestion are reduced while demand is not seriously affected, and airline profits are high.

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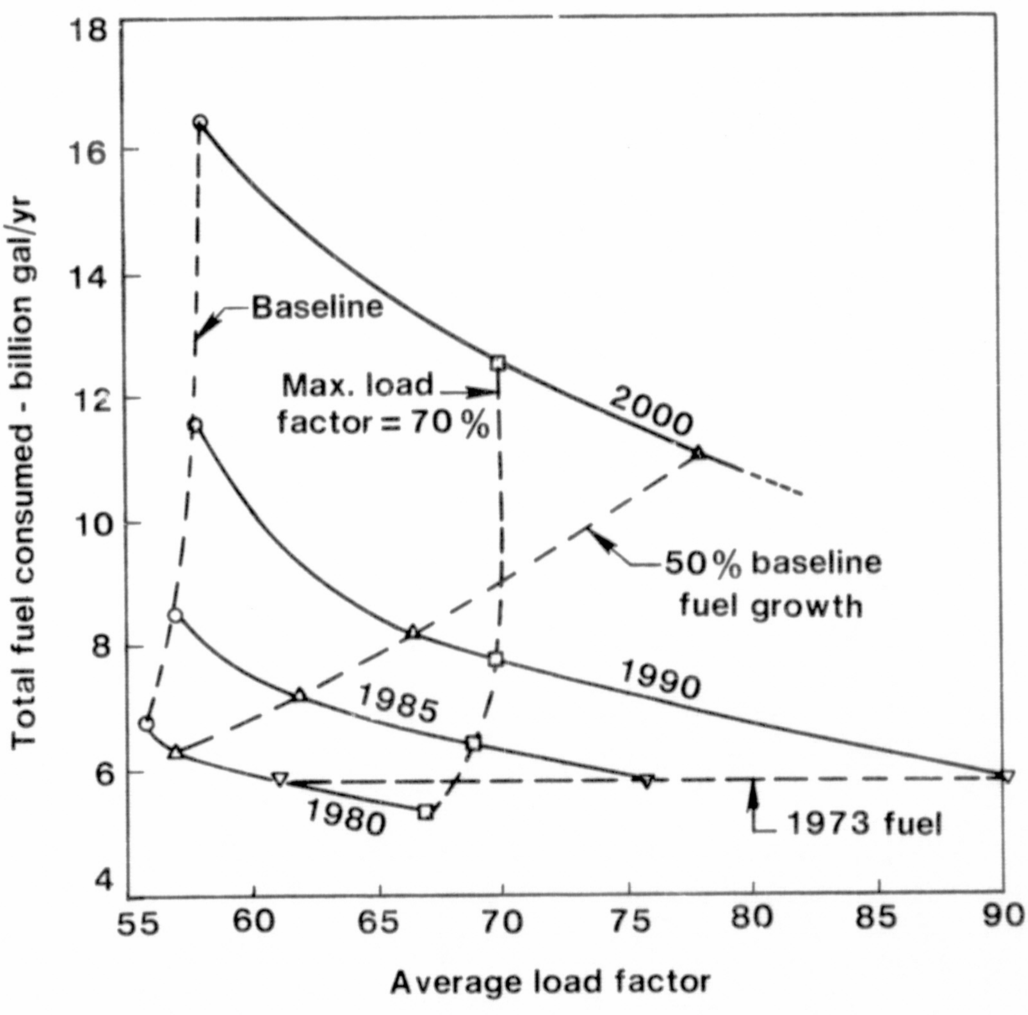
* Note that the fuel allocation scenarios do not appear in the same order in each forecast year in Table XII. Rather, they are placed in order of increasing fuel use. Also, the 70 percent load factor case with 12 percent system ROI is given only for 1980 because it is not a viable allocation scheme, as discussed in the text.

FUEL ALLOCATION SCENARIOS

Baseline fares
600 city-pairs



76–01–236–3

However, the frequency reductions and restraints on frequency growth would require a cooperative effort by carriers and government regulators. A substantial amount of government regulation, not only of capacity but also of the number of carriers in a given market, would probably be necessary. This, of course, represents a reversal of current proposals in government to deregulate and increase competition. Another problem posed by these scenarios is the necessity of avoiding fare reductions despite high airline profit levels. A possible solution would be a tax levied on the airlines (in addition to income tax which is included in the ROI computation). Such a tax would route the "excess" revenue to the government, from which it could be disbursed to fund fuel-conserving technology developments or to subsidize the price of synthetic fuels.

Finally, the inconvenience associated with lower frequencies, and fewer opportunities for nonstop travel, may not be fully reflected in the slight demand reduction. The UTRC demand model is sensitive to the travel time degradation caused by these changes, but there is nothing in the validation data base which specifically demonstrates sensitivity to structural changes such as reductions in connecting flights and competition.

Applicability of Fuel Allocation Scenario

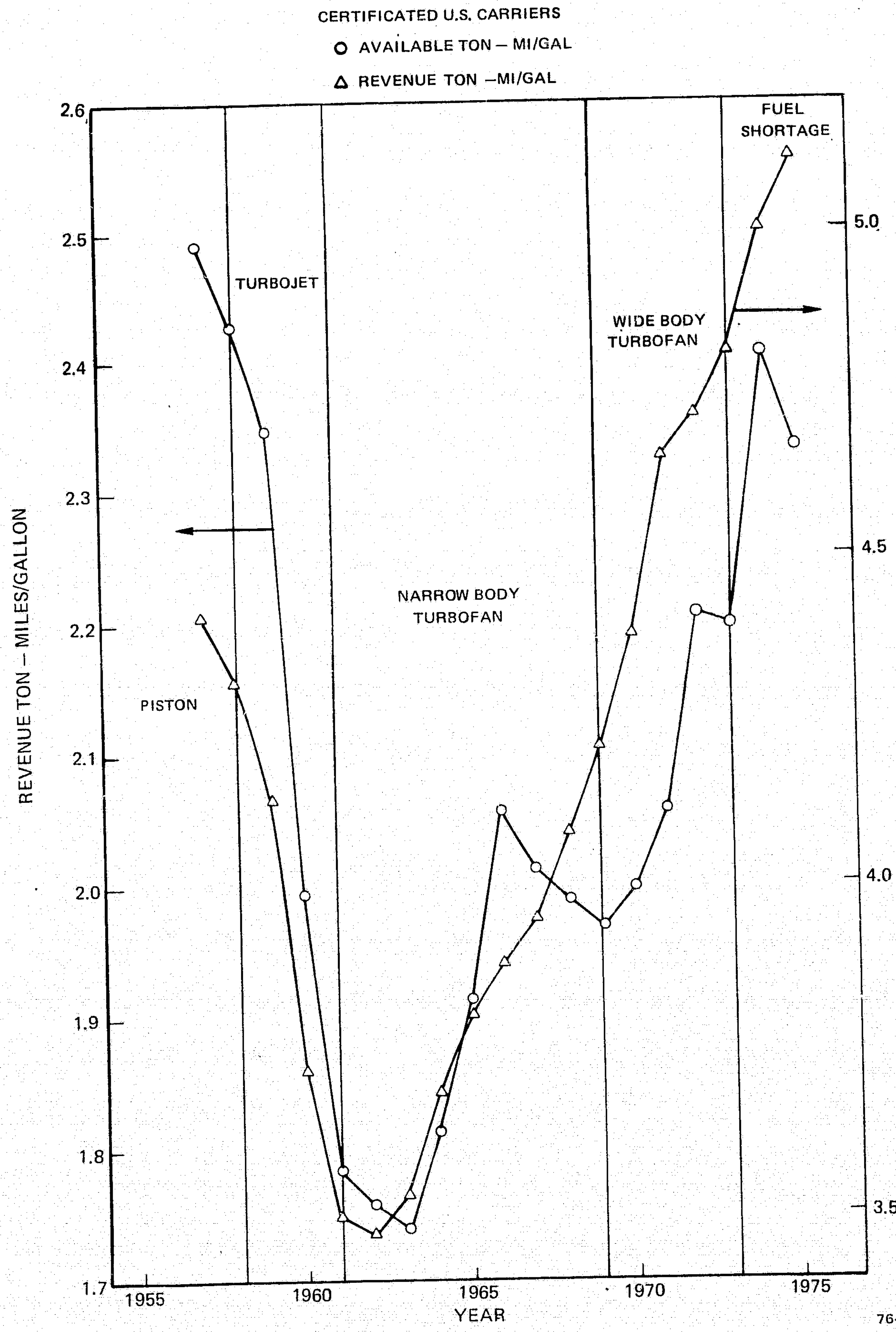
While fuel-allocation scenarios have been considered in only the baseline case (Option I) in this study, it is apparent that such measures could be considered in any of the fuel-conservation options (Options II to VI) with similar fuel-saving benefits.

Operational Procedures Options

The technology-oriented options necessarily involve lead times before their fuel-conservation benefits take effect. Much nearer-term savings, in some respects immediate, can be achieved by procedural changes in airline practice. Obvious measures include reduction of cruise speed, close management of fuel loads to avoid unnecessary "ferrying" of fuel, selective elimination of flights on low-load factor routes, reduction of ground and air delays, and more frequent engine maintenance. Measures such as these were voluntarily adopted by airlines to some extent even prior to the October 1973 oil embargo which resulted in fuel allocations due to the ensuing shortage in 1974.

A history of fuel efficiency of the U.S. certificated carriers is shown in Fig. 18 for a twenty-year period in which several basic, evolutionary changes were experienced. Beginning with the introduction of

U.S. FLEET FUEL EFFICIENCY



76–03–71–8

turbojets in 1958, fuel efficiency took a steep decline which was reversed, in 1963, with the introduction of (and conversion to) turbofans. As more turbofan-powered aircraft were added to the fleet, fuel efficiency increased through 1966. The decrease in fuel efficiency between 1966 and 1969 was not caused by any fleet innovations, but merely by an increase in service frequency which reduced load factor. A reversal in trend again occurred in 1969 when wide-body aircraft powered by higher-bypass engines appeared. By the end of 1973, the loss in available ton-miles per gallon experienced in the conversion from piston to jet power had been more than compensated, and a substantial part of the loss in revenue ton-miles per gallon had been recovered.

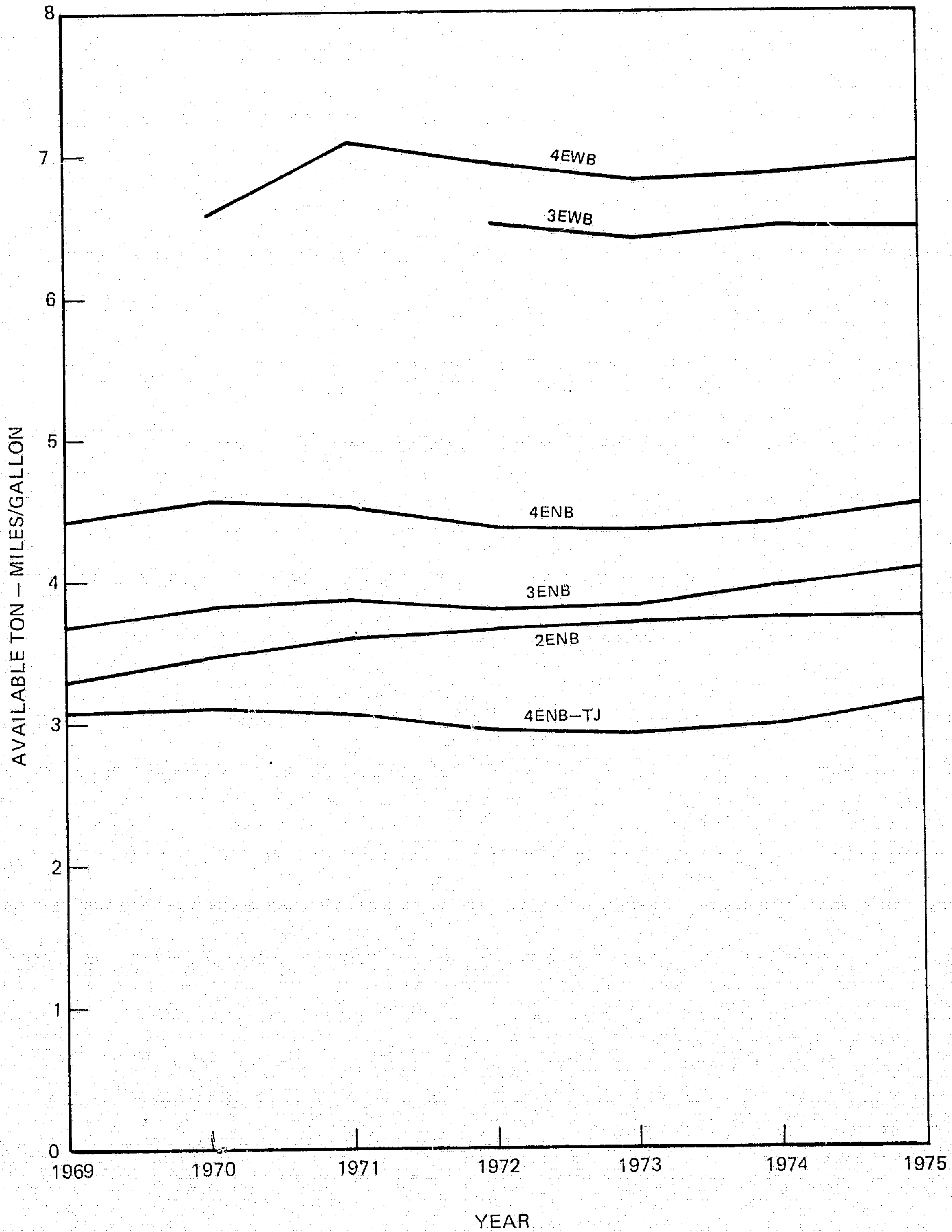
Immediately after the fuel embargo, load factor increases were effected by cutting back flight frequencies. In addition, continued changeover to wide bodies resulted in further fuel efficiency improvements (available ton-mi/gal). The most recent CAB data indicate that ton-mile load factors have fallen somewhat, although both measures of fuel efficiency in Fig. 18 have risen well above 1973 levels.

Although speed reductions and other fuel economy measures have been implemented, an indication that operating procedure improvements have not yet resulted in appreciable fuel savings is provided by Fig. 19 which shows fuel efficiency trends in various aircraft over recent years. Modest improvements were made between 1973 and 1975; however, most models have not achieved significantly better efficiency in the post-embargo period.

These results suggest that procedural improvements either cannot contribute appreciably to fuel conservation, or the kinds of improvements which could make measurable contributions have not yet been implemented. Since fuel prices rose steadily in 1974, the incentive for airlines to conserve fuel was there; however, the cost of implementing the most effective measures may still have been prohibitive relative to the fuel price increase which was incurred.

In this study, two categories of fuel improvements were considered: (1) procedural changes which could be effected with the current air traffic control (ATC) system, and (2) reductions in delay and holding times which could be achieved in a significantly improved ATC environment. Thus, the first category consists of measures which could be adopted almost immediately, while the ATC-dependent improvements are further in the future. The best judgment of the RECAT contractors was that these latter improvements should

FUEL EFFICIENCIES OF VARIOUS AIRPLANE TYPES
DOMESTIC PASSENGER SERVICE



76–03–71–22

not be counted on until 1985. The operational procedures options included only baseline aircraft models in order that the effect of the procedural improvements could be determined by direct comparison with the baseline case.

A complete itemization of near-term procedural changes, and the fuel savings they would promote, is given in Table XIII. The following list summarizes the procedures changes and gives the abbreviations used in the table.

Procedure Change	Abbreviation
Present ATC:	
Reduce cruise speed to Long Range Cruise	LRC
2000-ft Step Climb	Step Climb
Load for a 1% more Aft CG	AFT CG
Aerodynamic Cleanup	Aero
Reduce Operating Empty Weight by 1/2%	OEW
Improved Engine Standard	Engine
Improved ATC:	
Climbing Cruise	CL-CR
Reduced Delay in Holding	HOLD
Reduced Terminal Delay	TERM

Most of these items are self-explanatory, with the possible exception of the Improved Engine Standard. The fuel saving referred to involves improved maintenance to reduce sfc deterioration by 1/3 of the average in-service levels. Since the high-bypass ratio turbofans in service on wide-body aircraft have experienced more rapid deterioration than the earlier engines on narrow-body aircraft, the fuel savings in Table XIII are greatest for wide bodies.

There is a cost associated with implementation of the procedures changes in Table XIII, consisting partly of an incremental investment (assumed to be negligible) and partly due to the speed reduction which has the effect of increasing operating costs in spite of the fuel saving they achieve. This latter effect could have been eliminated by disregarding that part of the fuel advantage in Table XIII which comes from the speed reduction. However, the objective here is to estimate the total conservation potential of procedural improvements, particularly in the short term.

TABLE XIII

ESTIMATED FUEL SAVINGS BY PROCEDURAL IMPROVEMENTS

Percentage Reduction in Block Fuel

Aircraft Model*	Present ATC						Improved ATC		
	LRC	Step Climb	Aft CG	Aero	OEW	Engine	CL-CR	HOLD	TERM
Out of Production									
DC-9-10	0.4	0	0.2	0.4	0.1	0.5	0	1.5	2.6
B-727-100	0.2	0.1	0.2	0.5	0.2	0.5	0.1	1.0	1.7
DC-8-20	1.0	0.3	0.2	0.5	0.2	0.3	0.4	0.8	1.9
DC-8-50	1.0	0.3	0.2	0.5	0.2	0.3	0.4	0.8	1.9
DC-8-62	1.0	0.3	0.2	0.5	0.2	0.3	0.4	0.8	1.9
DC-8-61	1.0	0.3	0.2	0.5	0.2	0.3	0.4	0.8	1.9
In Production									
DC-9-30	0	0	0.2	0.4	0.15	0.5	0	1.6	2.5
B-737-200	0	0	0.2	0.4	0.15	0.5	0	1.7	2.7
B-727-200	0.2	0.1	0.2	0.5	0.25	0.5	0.1	1.1	1.7
DC-10/L-1011	1.0	0.3	0.2	0.5	0.2	1.0	0.4	0.7	1.0
B-747-200	1.2	0.5	0.2	0.5	0.25	1.0	0.5	0.4	0.5

* See Table IV for other aircraft represented by these models.

The results of Option IIa, as presented in Table XIV, give the fuel saving which might be attained by this means alone, irrespective of the fuel price and load factor variations which were considered in the fuel allocation scenarios. Obviously, combinations of the effects of these various alternatives could be used to represent more realistic future scenarios. Although such alternatives were beyond the scope of the RECAT program, the modeling techniques employed in the simulations are capable of treating any combination of the fuel-conservation options considered in this study.

Current ATC

Comparing Option IIa with the baseline results in Table XIV, it will be noted that the increase in operating costs and fares results in lower demand. The reduction is 5.7 percent in 1980 and decreases to 2.8 percent in 2000 because rising incomes overshadow the cost increase in later years. As a result of the depressed demand, annual fuel savings, ranging from 7.6 percent in 1980 to 5.9 percent in 2000, are overstated in the sense of the real efficiency gain. As shown, improvements in fuel efficiency (seat-mi/gal) are only 2.6 percent in 1980 and 3.3 percent in 2000.

Note that there is a minor change in fleet size between the baseline case and Option IIa, but a noticeable change in fleet composition, especially in 1980 and 1985. Several effects produce this change, none of which is dominant. The decrease in demand would tend to reduce fleet size; however, lower productivity due to the rise in block time offsets that tendency, and fleet size is actually larger in Option IIa. Also, the slower growth in demand has the effect of delaying the introduction of larger airplanes on all routes. Thus there is a shift away from wide bodies (relative to the baseline case), and the only types which appear in greater numbers in Option IIa are the 2ENBs, the smallest of the in-production models.

Advanced ATC

Although all aircraft types can expect to benefit from improvements in the ATC system, the primary mechanism of these improvements is in the elimination of unproductive time in the enroute and terminal phases of flight. Therefore, it is expected that these block time reductions will occur selectively with respect to route, benefits at major hubs being much larger than at less busy airports. Since the actual block time advantages of an improved ATC environment can only be estimated, the procedure followed in this study was to allow a five-minute reduction in block time at each of

TABLE XIV

OPERATIONAL PROCEDURES OPTION
(RECAT 600 City-Pair Network)

	1973 Baseline	1980 Baseline	1980 Present ATC IIa/IIb	1985 Baseline	1985 Present ATC IIa	1985 Advanced ATC IIb	1990 Baseline	1990 Present ATC IIa	1990 Advanced ATC IIb	2000 Baseline	2000 Present ATC IIa	2000 Advanced ATC IIb
Enplaned Air Pass.-Miles(10^9)	107.5	168.8	159.3	224.1	214.3	235.2	280.5	270.1	294.7	436.1	423.9	456.8
Fuel - Total (10^9 gals)	5.808	6.656	6.187	8.440	7.871	8.428	10.536	9.867	10.500	16.400	15.439	16.376
- Savings vs. baseline (%)	-	-	7.6	-	6.7	0.1	-	6.3	0.3	-	5.9	0.1
- Efficiency - pass. - mi/gal	18.51	25.37	25.74	26.56	27.22	27.90	26.62	27.37	28.07	26.59	27.46	27.90
- Efficiency - seat - mi/gal	36.15	45.53	46.72	46.32	47.67	48.61	46.17	47.52	48.48	45.86	47.34	48.19
- Efficiency - improvement vs. baseline (%)			2.6		2.8	4.9		3.0	5.1		3.3	5.1
Fares relative to 1973	1.000	0.995	1.036	0.957	0.986	0.920	0.950	0.975	0.912	0.937	0.955	0.900
Total flights/day	6615	7328	7158	8240	8067	8445	8959	8780	9164	11103	10938	11440
Load Factor (%)	51.2	55.7	55.1	57.3	57.1	57.4	57.7	57.6	57.9	58.0	58.0	57.9
Average stage length (mi)	639	660	661	677	674	674	712	710	708	745	744	740
Average block time - (hrs) (baseline average stage length)	1.64	1.68	1.76	1.71	1.80	1.67	1.79	1.87	1.75	1.87	1.94	1.82
Fleet size - total	1372	1549	1572	1771	1794	1779	1992	2016	1993	2557	2592	2571
- B-747	65	113	99	227	212	263	353	339	394	840	822	895
- DC-10/L-1011	100	240	227	340	332	336	455	444	454	651	633	640
- DC-8/B-707	356	55	58	0	0	0	0	0	0	0	0	0
- B-727-100/200	533	759	756	845	838	821	955	965	932	956	1024	956
- B-737-200/DC-9-10/30	305	378	429	360	414	358	228	269	213	110	113	79
- Turboprop	13	4	4	0	0	0	0	0	0	0	0	0

23 major hubs and no benefit elsewhere in the system. Thus, a route linking two major hubs would enjoy a ten-minute time advantage over the baseline block time, a route linking a major hub with a smaller city would benefit by only five minutes, and there would be no advantage on a route between two small cities. The average block time reduction was about 7 minutes, reflecting the preponderance of major hub routes.

Option IIb, which incorporates the advanced ATC assumptions, also includes the operational procedures changes in Option IIa. Therefore, since the impact of the improved ATC system does not appear until 1985, the two cases are identical in 1980 (see Table XIV). In the succeeding forecast years, the benefit of block time reductions with advanced ATC is seen to offset the penalty in Option IIa so that average block times in Option IIb are lower than in the baseline case. Lower costs and fares made possible by this improvement stimulate demand, resulting in almost no net saving in annual fuel usage. On a fuel efficiency basis, however, there is about a 5 percent improvement over the baseline case.

Retrofit and Modification Options

In the retrofit/modification options an attempt was made to determine the potential fuel saving and other system impacts which would occur if the baseline airplanes were modified and/or retrofitted* to reduce their fuel consumption. Only the baseline airplanes (see Table XV) were considered, and retrofits were divided into two groups: (1) those which involve only aerodynamic changes (referred to as Option IIIa) and (2) those which involve both aerodynamic and engine changes (Option IIIb).

All airplanes benefitted from the aerodynamic retro/mod package which involved a general drag reduction program and installation of winglets or wingtip extensions on existing aircraft (retrofit) as well as on future purchases (modification) of in-production models. The first retro/mod option, Option IIIa in Table I, consisted of these aerodynamic changes which resulted in the fuel saving, operating cost, and modification cost characteristics summarized in the first part of Table XV. In the second case, Option IIIb, all 4 ENB turbojet and turbofan aircraft were assumed to be reengined with JT8D-209 engines (refanned version) <u>in addition</u> to the aerodynamic changes of Option IIIa. Thus, IIIb differs from IIIa only in that DC-8 and B-707/720 aircraft benefit from this reengining. The latter part of Table XV shows the effects of this engine change on the airplanes to which it is applied.

The baseline retirement schedules for the out-of-production aircraft were modified by extending the life of retrofitted aircraft by three years (five years for reengined aircraft). However, since it was assumed that the retrofit program will not start until 1978, baseline retirement schedules were used from 1973 to 1978, thereby resulting in a relatively small number of out-of-production aircraft remaining in 1980 and 1985. In order to cover the possibility that retirements may proceed more slowly than the rate assumed in the baseline, an additional pair of options was run in which it was assumed that no aircraft were retired between 1975 and 1978. The options using the projected retirements until 1978 are referred to as $IIIa_1$ and $IIIb_1$ while those assuming no retirements prior to 1978 are $IIIa_2$ and $IIIb_2$. A summary of retirement schedules for out-of-production aircraft in all options is given in Table XVI.

The results of the four forecasts are compared with the baseline case in Table XVII, with emphasis on each option's fuel saving relative to the

*Retrofit refers to changes in airplanes already in service; modification refers to the same changes as applied to future deliveries of in-production airplanes.

TABLE XV

CHANGES IN AIRCRAFT PARAMETERS USED IN
RETROFIT/MODIFICATION OPTIONS

	Fuel Saving (%)	Operating Cost Increase ($/Block Hr.)	Cost of Modifications ($$10^6$)
Aerodynamic Retrofit (Option IIIa)			
B-747	7.5	5	0.25
DC-10/L-1011	7.5	6	0.25
B-727-100/200, B-737-200, DC9-10/30	4.0	1	0.08
DC-8-20/30	5.0	3	0.15
DC-8-50/B-707-100/B-720B	5.0	4	0.15
DC-8-61	5.0	4	0.15
DC-8-62/B-707-300	2.0	6	0.15
Aerodynamic & Engine Retrofit (Option IIIb)			
DC-8-20/30	28.0	97	4.65
DC-8-50/B-707-100/B-720B	15.0	126	4.87
DC-8-61	15.0	99	4.87
DC-8-62/B-707-300	12.0	189	4.87

Notes: All aerodynamic modifications complete by 1980 except 37% of B-727-100.
All engine modifications complete by 1980 except 18% of DC-8-20/30 and 17% of DC-8-61.
Operating cost increase is exclusive of cost of fuel saved.

TABLE XVI

OUT-OF-PRODUCTION AIRCRAFT FLEET SIZE VS. YEAR
(REFLECTING DIFFERENT RETIREMENT SCHEDULES)

600 CITY-PAIRS

Baseline: Options I and $IIIa_0$

Fleet Size

	1973	1975	1980	1985
4ENB	356	275	55	0
B727-100	286	286	140	0
DC9-10	46	35	10	0
Turboprop	13	4	4	0
Total	701	600	209	0

Aerodynamic Retrofits and Modifications: Options $IIIa_1$ and $IIIa_2$

	1980		1985	
Option	$IIIa_1$	$IIIa_2$	$IIIa_1$	$IIIa_2$
4ENB	115	275	27	102
B727-100	183	286	102	160
DC9-10	20	35	0	16
Turboprop	4	4	0	0
Total	322	600	129	278

Aerodynamic and Engine Retrofits and Modifications: Options $IIIb_1$ and $IIIb_2$

	1980		1985	
Option	$IIIb_1$	$IIIb_2$	$IIIb_1$	$IIIb_2$
4ENB	115	275	55	177
B727-100	183	286	102	160
DC9-10	20	35	0	16
Turboprop	4	4	0	0
Total	322	600	157	353

TABLE XVII

AIRCRAFT RETROFIT/MODIFICATION OPTIONS
(RECAT 600 City-Pair Network)

	1973	1980						1985					
			Aero (In-Prod. Only)	Proj. Retirements		No 75-80 Retirmts.			Aero (In-Prod. Only)	Proj. Retirements		No 75-80 Retirmts.	
		Baseline	$IIIa_0$	Aero $IIIa_1$	Aero & Eng. $IIIb_1$	Aero $IIIa_2$	Aero & Eng. $IIIb_2$	Baseline	$IIIa_0$	Aero $IIIa_1$	Aero & Eng. $IIIb_1$	Aero $IIIa_2$	Aero & Eng. $IIIb_2$
Enplaned Pass. Miles (10^9)	107.50	168.83	170.01	170.86	168.94	170.00	165.47	224.14	225.31	225.07	224.34	224.60	222.21
Fuel: Total (10^9 gals/yr)													
Savings vs. Baseline (%)	[illegible]	6.656	6.356	6.436	6.329	6.701	6.403	8.440	7.987	8.078	8.060	8.176	8.100
Actual – Annual	--	--	4.5	3.3	4.9	-0.7	3.8	--	5.4	4.3	4.5	8.1	4.0
– Cumulative Since 1973	--	--	1.2	0.9	1.3	-0.2	1.0	--	2.9	2.2	2.8	0.7	2.3
Adjusted – Annual	--	--	5.2	4.5	5.0	0	1.9	--	5.9	4.7	4.6	3.3	3.2
– Cumulative Since 1973	--	--	1.4	1.2	1.3	0	0.5	--	3.2	2.7	2.8	1.0	1.5
Efficiency: Pass.-Mi./Gal	15.51	25.37	26.75	26.55	26.69	25.37	25.84	26.56	28.21	27.86	27.83	27.47	27.43
Seat-Mi/Gal	36.1	45.5	46.0	47.1	47.4	44.4	45.5	46.3	49.3	48.6	48.4	47.7	47.5
Fares vs. 1973	1.000	0.995	0.988	0.984	0.995	0.990	1.014	0.956	0.951	0.952	0.956	0.955	0.966
Total Flights/Day	6615	7328	7351	7411	7373	7548	7454	8240	8251	8319	8315	8381	8317
Load Factor (%)	[illegible]	55.7	55.7	56.4	56.3	57.1	56.8	57.3	57.3	57.4	57.5	57.6	57.8
Emissions (10^3 Wtd. Tons)	[illegible]	36.259	36.552	37.131	36.506	36.292	36.879	46.700	47.093	47.516	47.328	48.023	47.536
Noise vs. 1973	1.000	0.862	0.865	0.941	0.875	1.076	0.901	0.958	0.958	0.990	0.980	1.027	0.978
Fleet Size: Total	1372	1549	1553	1561	1554	1586	1565	[illegible]	1773	1782	1783	1797	1784
B-747	65	113	114	130	124	139	131	[illegible]	229	251	246	241	247
DC-10/L-1011	[illegible]	240	246	207	206	139	135	[illegible]	346	305	296	292	257
DC-8/B-707/B-720[1]	356	55	55	115	115	275	275	0	0	27	55	102	177
B-727-200	247	619	622	561	557	410	396	845	847	769	757	696	635
B-727-100[1]	286	140	140	183	183	286	286	0	0	102	102	160	160
B-737-200/DC-9-30	259	365	360	341	344	298	303	360	350	328	327	291	292
DC-9-10[1]	46	[illegible]	[illegible]	20	20	35	35	0	0	0	0	16	16
Turboprop[1]	13	4	4	4	[illegible]	4	4	0	0	0	0	0	0
New Aircraft Investment[2]: Since Previous Forecast (10^9\$)	12.749	7.932	8.244	7.303	7.601	4.671	5.432	7.836	7.962	7.919	7.690	9.202	8.678
Cumulative Present Value (10^9\$)	—	5.90	6.124	5.422	5.576	3.461	3.866	9.551	9.834	9.112	9.174	7.749	7.918

[1] fixed fleet size [2] includes cost of retrofitting existing aircraft

TABLE XVII (cont'd)

AIRCRAFT RETROFIT/MODIFICATION OPTIONS
(RECAT 600 City-Pair Network)

	1990						2000					
		Aero (In-Prod. Only)	Proj. Retirements		No 75-80 Retirements			Aero (In-Prod. Only)	Proj. Retirements		No 75-80 Retirements	
	Baseline	$IIIa_0$	Aero $IIIa_1$	Aero & Eng. $IIIb_1$	Aero $IIIa_2$	Aero & Eng. $IIIb_2$	Baseline	$IIIa_0$	Aero $IIIa_1$	Aero & Eng. $IIIb_1$	Aero $IIIa_2$	Aero & Eng. $IIIb_2$
Enplaned Pass. Miles (10^9)	280.45	282.36	281.54	281.35	279.97	278.70	436.13	439.05	439.09	439.14	439.32	439.48
Fuel: Total (10^9 gals/yr)	10.536	9.940	9.838	9.823	9.737	9.720	16.400	15.421	15.337	15.319	15.252	15.200
Savings vs. Baseline (%)												
Actual - annual	--	5.7	6.6	6.8	7.6	7.7	--	6.0	6.5	6.6	7.0	7.3
- cumulative since 1973	--	3.8	3.5	3.9	2.6	3.8	--	4.9	5.0	5.3	4.9	5.6
Adjusted - annual	--	6.3	7.0	7.1	7.4	7.2	--	6.6	7.1	7.2	7.7	8.0
- cumulative since 1973	--	4.3	3.9	4.0	2.7	3.0	--	5.4	5.5	5.6	5.2	5.4
Efficiency: Pass-Mi/gal	26.62	28.40	28.62	28.64	28.75	28.67	26.59	28.47	28.63	28.67	28.80	28.91
Seat-Mi/gal	46.2	49.2	49.6	49.7	50.0	50.1	45.9	49.1	49.3	49.4	49.6	49.8
Fares vs. 1973	0.950	0.943	0.946	0.947	0.951	0.955	0.937	0.928	0.930	0.930	0.930	0.929
Total flights/day	8959	8972	8950	8931	8891	8800	11103	11159	11275	11276	11336	11206
Load factor (%)	57.7	57.8	57.7	57.7	57.5	57.3	58.0	58.0	58.0	58.1	58.1	58.1
Emissions (10^3 wtd. tons)	59.080	59.559	59.715	59.743	59.765	60.001	92.875	93.594	93.793	93.787	93.878	93.981
Noise vs. 1973	1.059	1.068	1.050	1.052	1.043	1.026	1.213	1.210	1.207	1.210	1.203	1.181
Fleet Size: Total	1992	1994	1985	1982	1974	1956	2557	2568	2590	2590	2593	2555
B-747	353	359	332	326	297	300	840	854	811	802	774	783
DC-10/L-1011	455	458	507	518	565	579	651	642	700	713	761	780
DC-8/B-707/B-720[1]	0	0	0	0	0	0	0	0	0	0	0	0
B-727-200	955	963	942	942	931	900	956	971	971	975	946	886
B-727-100[1]	0	0	0	0	0	0	0	0	0	0	0	0
B-737-200/DC-9-30	228	214	205	197	181	176	110	100	107	101	113	105
DC-9-10[1]	0	0	0	0	0	0	0	0	0	0	0	0
Turboprop[1]	0	0	0	0	0	0	0	0	0	0	0	0
New aircraft investment[2]:												
Since previous forecast (10^9\$)	13.877	14.069	14.944	15.364	15.913	16.995	30.256	30.822	29.929	29.549	28.693	27.852
Cumulative present value (10^9\$) (8% discount)	13.951	14.295	13.651	14.046	12.795	13.307	19.436	19.883	19.277	19.404	17.997	18.357

[1] fixed fleet size [2] includes cost of retrofitting existing aircraft

baseline. Annual fuel savings are shown for each forecast year, as well as cumulative savings from 1973 through each forecast year. Because revenue is balanced against cost to achieve a 12 percent system ROI, each option has a slightly different (generally lower than the baseline) fare level and, as a result, a different level of demand (enplaned pass-miles). To put each option on a common basis for comparison, adjusted fuel savings were computed by dividing the fuel efficiency (pass-mi/gal) of each option into the baseline enplaned passenger-miles and comparing with the baseline fuel. The demand-adjusted fuel savings are shown in Table XVII for each option on both an annual and a cumulative basis. In addition, the adjusted fuel savings are shown graphically in Figs. 20 (annual) and 21 (cumulative).

Options $IIIa_1$ and $IIIb_1$ offer greater fuel savings in 1980 and 1985 than the subscript 2 (delayed retirement) options ($IIIa_2$ and $IIIb_2$, respectively), particularly on an adjusted basis. This is because, in each option, the potential fuel saving from improvements to the in-production aircraft (B-747, DC-10, L-1011, B-727-200, B-737-200, DC-9-30) are to some degree offset by the retention of larger numbers of out-of-production aircraft (DC-8, B-707, B-720, B-727-100, DC-9-10) which are less fuel-efficient than the in-production airplanes even after retrofit. Since the subscript 2 options retain more out-of-production aircraft than subscript 1 options, this phenomenon is more pronounced.

This observation suggests that greater fuel saving might be achieved by modifying only the in-production aircraft and allowing the others to be retired as per the (more rapid) baseline schedule, hence defining an additional option referred to as Option $IIIa_0$. (Note that there is not an equivalent b option since only in-production aircraft are being modified.) Results for this option are shown in Table XVII and Figs. 20 and 21. It can be seen that this option does indeed offer superior fuel savings in 1985 and is comparable, in 1980, to the best option ($IIIb_1$) of the four originally considered.

Within each retirement assumption, the aero-plus-engine options appear to offer greater 1980 fuel savings than the aero-alone options because of the improved fuel efficiency of the reengined 4ENB aircraft. A comparison of the adjusted savings, shown in Figs. 16 and 17, however, reveals that much of these savings is due to the suppressed demand resulting from the higher fares of the aero + engine options, which is a result of the higher operating and capital costs of the reengined 4ENB aircraft. In 1985, the aero + engine adjusted savings are slightly less than the aero-alone savings because the aero + engine options retain more 4ENB aircraft than the aero-alone options. Even though they have been reengined, they are still less efficient than the new aircraft which replace them in the aero-alone options.

ANNUAL ADJUSTED FUEL SAVING

OPTION IIIa1 – AERO MODS. PROJECTED RET'M
IIIa2 – AERO MODS, DELAYED RET'M
IIIa0 – AERO MODS, ONLY IN – PRODUCTION AIRCRAFT
IIIb1 – AERO + ENGINE MODS, PROJECTED RET'M
IIIb2 – AERO + ENGINE MODS, DELAYED RET'M

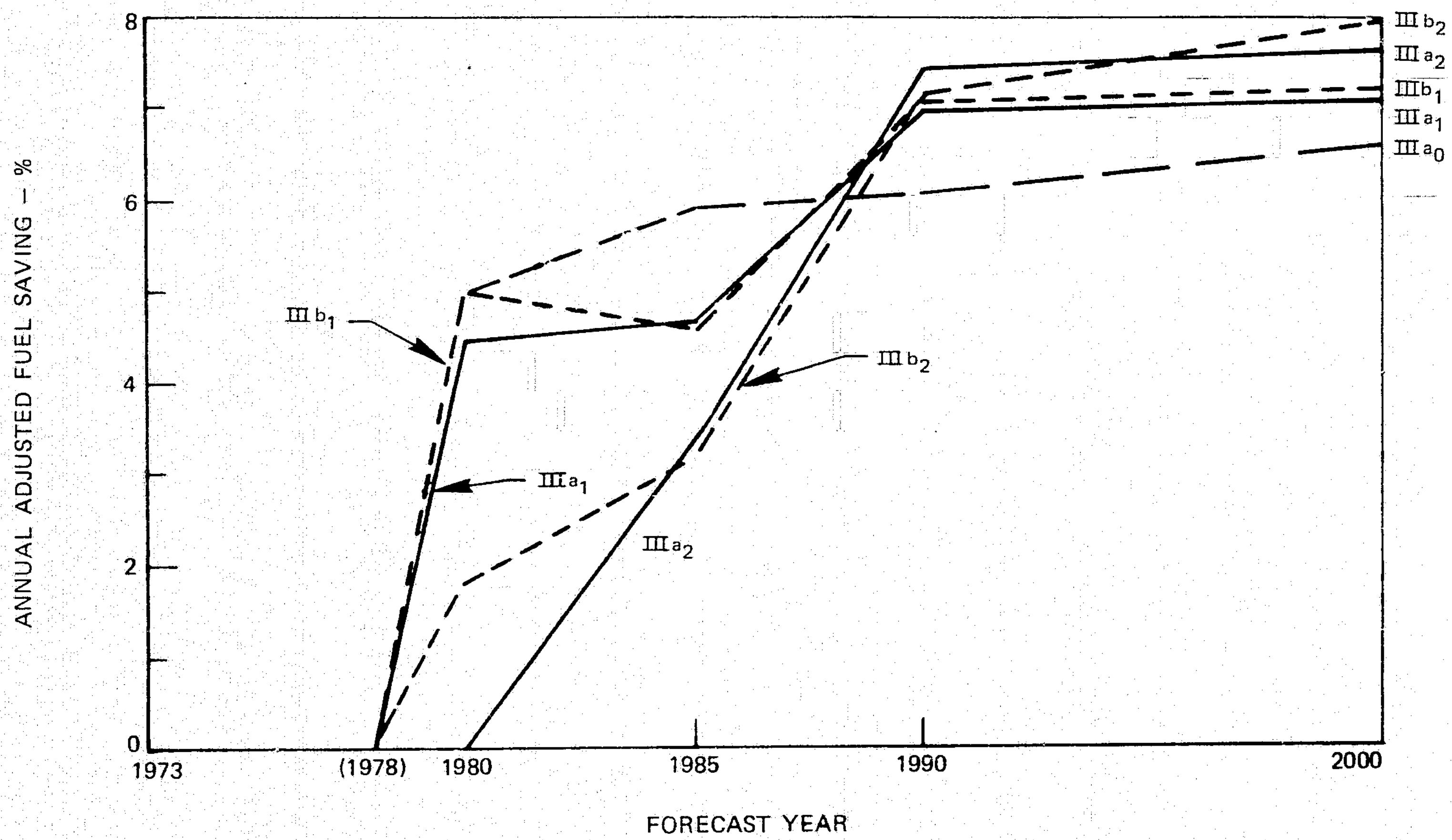
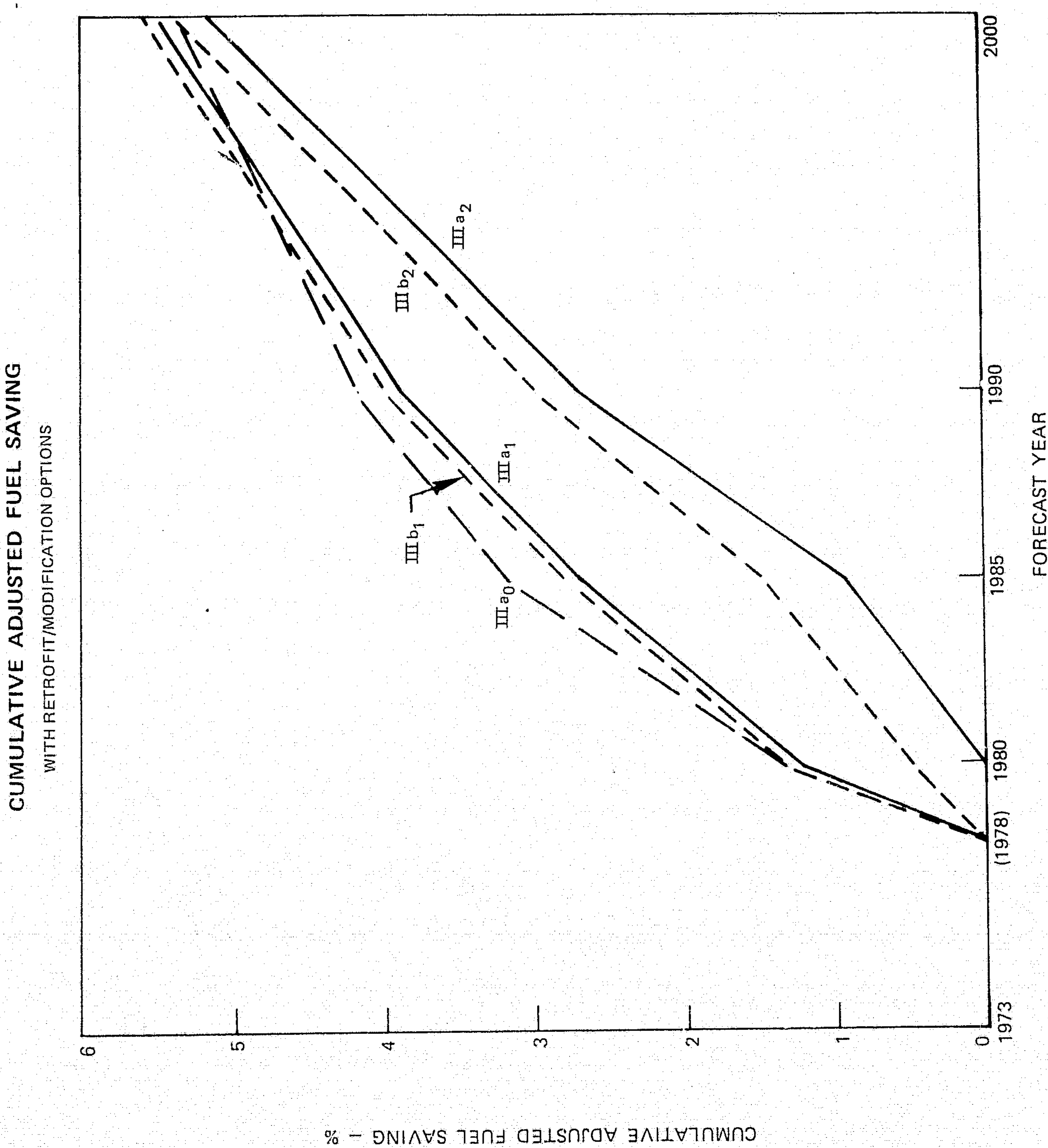


FIG. 20

76-01-144-1


CUMULATIVE ADJUSTED FUEL SAVING
WITH RETROFIT/MODIFICATION OPTIONS
III a$_2$
III b$_2$
III a$_1$
III b$_1$
III a$_0$
1973
(1978)
1980
1985
1990
2000
FORECAST YEAR
0
1
2
3
4
5
6
CUMULATIVE ADJUSTED FUEL SAVING – %

After 1985, all four basic scenarios show substantially increased fuel savings because of the retirement of all out-of-production aircraft. These exceed the $IIIa_0$ savings because of lower ratios of B-747 to DC-10/L-1011 (3EWB) aircraft. (The latter are more fuel-efficient than the former, particularly at short stage lengths.) This is a reversal of the situation in 1980 and 1985, when the B-747/3EWB ratio is higher for each of the four basic scenarios than for the baseline. In 1980 and 1985, the B-747 aircraft fleets are larger than in the baseline because, on many routes, the retention of more older (and smaller) aircraft raises the required ratio of seats to frequencies to be provided by new aircraft. This results in a greater preference for larger new aircraft. Between 1985 and 1990, however, the rapid retirement of the retained older aircraft reverses the situation. More frequencies must be replaced than in the baseline, while the number of seats to be added has not increased proportionately. Thus, the seat/frequency ratio is lower, and the smaller 3EWB aircraft are assigned in greater numbers. Although the subscript 2 options offer slightly greater adjusted fuel savings in 1990 and 2000, the subscript 1 options retain a slight advantage in cumulative adjusted savings. The $IIIa_0$ option has the highest cumulative savings through 1990.

Other differences among the options are also worth noting. All retro/mod options exhibit higher load factors than the baseline in 1980 and, to a lesser extent, 1985. This is because of the retention of 4ENB aircraft, which on longer routes (beyond B-727-200 range) would have to be replaced by wide-body aircraft, as in the baseline case. Since the 3EWBs are generally too large on these routes, baseline load factors are affected adversely. This advantage in load factor contributes to the fuel savings discussed above. Because more older, smaller aircraft are in use, these options require more flights than the baseline in 1980 and 1985, but not enough to cause congestion problems.

Four of the five retro/mod options require less investment in new aircraft than the baseline case (including the cost of retrofitting existing aircraft) in the 1973-1980 period. This is particularly true of the subscript 2 options, where the lower investment levels result from postponed retirements, so that larger investments are required after 1980. The aero + engine options require more capital than the aero-alone because of the high reengine cost. Thus, the cumulative present values (using 8 percent annual discount) of the various investment patterns through the year 2000 may not be substantially different than the baseline, and are in some cases lower, although these amounts do not reflect possible differences among the options in the depreciated value of the equipment on hand in 2000.

Since the options which involve the largest investments (see Table XVII) also achieve the greatest savings in fuel, a trade-off between fuel saved and relative investment is suggested. In Fig. 22 all five retro/mod options are presented in a plot of adjusted cumulative fuel saved vs. cumulative present value saved, where the saving in each instance is relative to the baseline case. Since the set of options is not characterized by continuity of these parameters, the locus of points for each option deviates from a smooth curve. In particular, year-to-year variations in the fleet for all but the $IIIa_0$ option are drastic enough to cause significant deviations in cumulative present value. Therefore, the points have not been joined. However, the general trends in each forecast year have been highlighted by the shaded regions bounding each set of points.

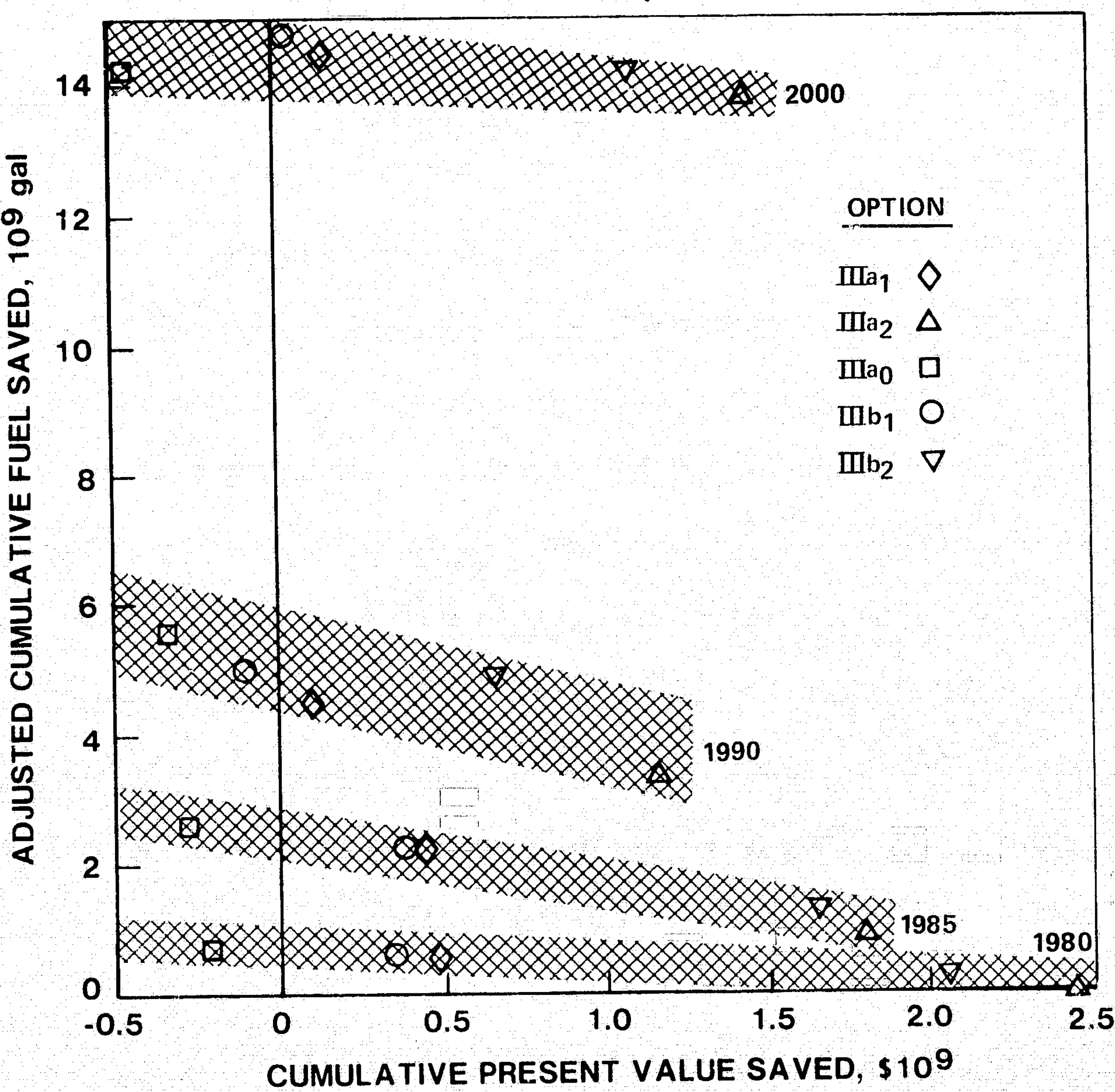
Based on the trends in Fig. 22 it appears that the choice among the five retrofit/modification options is very much dependent on the desired goal, especially with respect to near-term and far-term fuel savings. In 1980, for example, the choice ranges between Option $IIIa_0$, in which a modest saving in cumulative fuel of 0.6×10^9 gallons can be achieved at an expense in cumulative present value of $\$0.22 \times 10^9$, and Option $IIIa_2$, in which no fuel is saved, but cumulative present value of the fleet is reduced by almost $\$2.5 \times 10^9$. Any trade-off between these extremes can be had by adjusting the retirement rates and degree of retrofit of older-model aircraft.

Similar results occur in 1985 and 1990, except that the spread in cumulative fuel saved in each case is greater than in 1980, and the spread in cumulative present value is less. Thus, on the basis of the 1990 results, for example, there appears to be a real choice between saving fuel and saving investment dollars--2.2×10^9 gal vs. $\$1.5 \times 10^9$ between Options $IIIa_2$ and $IIIa_0$. In the distant future, as represented by the year 2000, differences in cumulative fuel savings become relatively small, whereas the spread in cumulative present value remains large. Therefore, a policy based on these far-term results would probably favor the minimum-investment alternative, Option $IIIa_2$, in which older aircraft retirements are delayed and retrofits do not include reengining of 4ENB aircraft.

However, in evaluating these options, emphasis should probably be placed on the near-term results (through 1985) because the likely availability of new or derivative aircraft types by 1990 would invalidate these particular 1990 and 2000 forecasts, and also because more confidence must necessarily be placed in the near-term forecasts. From a total system point of view, the $IIIa_0$ option (aerodynamic modification of only the in-production aircraft) may be preferable because of fuel, noise, and emissions advantages. In this case, out-of-production aircraft, particularly the 4ENB's, would be retired as rapidly as possible and modifications confined to the more efficient

SUMMARY OF RETROFIT / MODIFICATION OPTIONS

ALL SAVINGS RELATIVE TO BASELINE CASE



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in-production types. However, the decision of when to retire the aircraft may well be an investment decision based on a narrower perspective. The financial benefits of a near-term reduction in new aircraft investment could well result in lower retirement rates (i.e., the subscript 2 options) in which case retrofitting is definitely preferable. Then the aerodynamic-plus-engine retrofit program would be more desirable than aerodynamic retrofits only, particularly if large numbers of 4ENB aircraft remain in the fleet.

Derivative Aircraft Options

A total of eight aircraft designs was generated for the derivative aircraft options. These airplanes, whose characteristics are summarized in Table IV, include three variants of the DC-9; the B-727-300; two variants of the DC-10; and two variants of the L-1011. Basically, the DC-9 derivatives featured seating capacities equal to or larger than the DC-9-30, while the DC-10 and L-1011 derivatives consisted of one stretched version and one shortened version of each type.

It was apparent from the results of the UAL economic screen and the airplane cost and performance data that most of these derivatives did not look attractive enough to justify retention in the study. As shown in Figs. 11 to 13, the characteristics of many derivatives are poor relative to baseline in-production models. The aircraft assignment algorithm selects airplanes on the bases of capacity and 15 percent ROI load factor; if two airplanes have identical capacities and one attains a 15 percent ROI at a lower load factor for all stage lengths because of its superior economics, the other airplane will never be assigned even though it may be more fuel-efficient. Two derivatives, the DC-9-30D3, and the L-1011 Short Body were dropped specifically for this reason. Furthermore, it was found that three other derivatives, the DC-9-30D2, the B-727-300, and the DC-10-40D, were assigned to only a few routes; therefore, these airplanes were also omitted.

Thus, of the eight proposed derivatives, only three appear in the forecasts: the DC-9-30D1, the DC-10-10D, and the L-1011L. Each of these aircraft occupies a unique place in the spectrum of seating capacities and competes well, economically, with the baseline in-production airplanes. Consequently, these derivatives quickly established themselves in the fleet, starting with the 1985 forecast, as shown in Table XVIII.

Of the three aircraft, the L-1011L was found to be particularly attractive because: (1) it has a very large capacity (400 seats); (2) its very low purchase price gave it the lowest 15 percent ROI load factor over a wide range of short and intermediate distances; and (3) its good fuel efficiency

TABLE XVIII

DERIVATIVE AND NEW NEAR-TERM TURBOFAN AIRCRAFT OPTIONS
(RECAT 600 City-Pair Network)

	1973	1980	1985				1990				2000			
		Baseline	Baseline	Derivatives	(No L-1011L)	New Near-Term	Baseline	Derivatives	(No L-1011L)	New Near-Term	Baseline	Derivatives	(No L-1011L)	New Near-Term
				(IVa)	(IVb)	(V)		(IVa)	(IVb)	(V)		(IVa)	(IVb)	(V)
Enplaned Pass.-Miles (10^9)	107.50	168.83	224.14	225.29	223.01	228.77	280.45	283.71	279.20	293.15	436.1[illegible]	440.80	432.27	461.68
Fuel: Total (10^9 gals)	5.808	6.656	8.440	7.961	8.299	8.031	10.536	9.494	10.256	9.531	16.400	13.751	16.007	13.810
Savings vs Baseline (%)														
Actual	-	-	-	5.7	1.7	4.8	-	9.9	2.7	9.5	-	10.2	2.4	15.8
Adjusted	-	-	-	6.2	1.2	6.8	-	10.9	2.2	13.5	-	17.1	1.5	20.5
Efficiency: Pass-mi/gal	18.51	25.37	26.56	28.30	26.87	28.48	26.62	29.88	27.22	30.76	26.59	32.06	27.00	33.43
Seat-mi/gal	36.15	45.53	46.32	49.25	46.80	49.68	46.17	51.54	46.95	53.13	45.86	55.19	46.47	57.57
Improvement vs Baseline	-	-	-	6.3	1.0	7.3	-	11.6	1.7	15.1	-	20.3	1.3	25.5
Fares Relative to 1973	1.000	0.995	0.957	0.950	0.960	0.933	0.950	0.939	0.956	0.902	0.937	0.922	0.947	0.867
Load Factor (%)	51.2	55.7	57.3	57.4	57.4	57.4	57.7	58.0	58.0	57.9	58.0	58.1	58.1	58.1
Flights/Day	6615	7328	8240	8122	8288	7989	8959	8895	9084	8685	11103	10901	11259	10883
Average Capacity - Seats/Flight	136	172	192	194	191	200	209	211	206	222	249	257	248	269
Fleet Size: Total	1372	1549	1771	1756	1777	1739	1992	1986	2009	1961	2551	2515	2570	2542
B-747	65	113	227	137	220	[illegible]	353	137	337	62	840	231	834	50
DC-10/L1011	[illegible]	240	340	274	317	298	455	262	363	328	651	294	451	370
B-727-200	247	619	845	738	745	700	955	774	757	665	956	597	580	481
B-737-200/DC-9-30	259	368	360	332	334	343	228	158	162	196	110	51	54	84
Other[1]	701	209	0	0	0	0	0	0	0	0	0	0	0	0
DC-9-30D1	-	-	-	109	110	-	-	220	216	-	-	275	282	-
DC-10-10D	-	-	-	38	52	-	-	153	175	-	-	339	369	-
L-1011-Long Body	-	-	-	128	0	-	-	281	0	-	-	726	0	-
N8C-200-I	-	-	-	-	-	141	-	-	-	369	-	-	-	639
N80-400-L	-	-	-	-	-	136	-	-	-	341	-	-	-	917
New Aircraft Investment: (10^9\$)														
Since Previous Forecast	12.749	7.932	7.836	7.956	8.077	9.215	13.877	14.036	14.299	15.795	30.256	30.232	31.179	34.770
Cumulative 1973 Present Value (8% Discount)	-	5.900	9.551	9.607	9.663	10.193	13.951	14.058	14.197	15.202	19.436	19.539	19.850	21.506

[1] DC-8, DC-9-10, B-707, B-720, B-727-100, CV-880, Turboprops

at short and intermediate stages (see Figs. 11 and 12, pgs. 51 and 52) makes it a good alternative to the B-747 on dense routes. By the year 2000, the L-1011L became the most numerous single airplane type in the fleet.

The basic derivative option, referred to as Option IVa in Table XVIII, resulted in some significant fuel savings relative to the baseline case. Annual fuel savings ranged from about 6 percent in 1985 to 17 percent in 2000, both figures being adjusted for the effect of slightly increased demand in Option IVa. As shown in Table XVIII, these savings are achieved by a significant improvement in fuel efficiency when the baseline in-production airplanes are displaced by the derivatives in the future fleet.

There are no adverse effects caused by the changeover to derivative aircraft. Therefore, it can be concluded that Option IVa constitutes an acceptable long-range strategy for saving fuel because it achieves this objective without any notable cost or degradation in system performance. Only the absence of a short-term (pre-1985) benefit detracts from the value of Option IVa.

Of the three derivatives in Option IVa, the DC-9-30D1 represents the smallest departure from a basic design, while the DC-10-10D is a significant departure, featuring both a reduction in size and number of engines from the DC-10. However, it appears that the L-1011L is the most unusual derivative, because the stretched capacity of this airplane was achieved by a direct trade-off of passenger payload for fuel. Thus, the L-1011L has the same takeoff gross weight as the L-1011, but its maximum stage length is down from 3240 mi to 2095 mi. The L-1011L therefore occupies a unique position; it is either a very large replacement for the B-727-200, or a replacement for the DC-10/L-1011 and B-747 on high-density short-and intermediate-range routes. Moreover, it is apparent from Figs. 11 to 13 that the L-1011L is clearly the most attractive of all the derivatives.

On the basis of the results in Option IVa the L-1011L design approach appears to be a superior derivative concept. However, much of its advantage stems from its very low purchase price. In terms of $/seat, the L-1011L is far less expensive than the other derivatives, and is even less expensive than the wide-body in-production airplanes (see Table IV). Whether the pricing policy that leads to this disparity is realistic may be open to question, and if it is not realistic, then much of the fuel saving in Option IVa is not valid.

A second derivative option, Option IVb, was simulated to determine what changes would ensue if the L-1011L were omitted. Even without the L-1011L, the five derivatives eliminated in Option IVa were still not viable aircraft

because they fail to compete successfully against the in-production models. Therefore, Option IVb involves only two derivatives--the DC-9-30D1 and the DC-10-10D.

As indicated in Table XVIII, the effect of removing the L-1011L is to shift the fleet back to dependence on the B-747 for the highest-density routes. The DC-10-10D appears in slightly greater numbers, but its effect is small. For the most part, the routes captured by the L-1011L in Option IVa revert back to in-production aircraft in Option IVb. A consequence of this shift is the dramatic decrease in fuel saved relative to Option IVa. Without the fuel-efficient L-1011L on short- and intermediate-range routes, the existing wide bodies must be used, as they were in the baseline case. Thus it is seen that the large fuel savings in Option IVa were almost entirely a consequence of the L-1011L, even though fairly large numbers of the other derivatives were assigned in Option IVb.

New Near-Term Aircraft Option

According to the study ground rules, the new near-term aircraft were based on current technology in order that availability in the early 1980s would be assured. As with the derivatives, the first forecast year in which these new airplanes were assumed to be available is 1985.

There were three groups of new near-term designs considered in this study: 200-seat/intermediate range; 200-seat/long range; and 400-seat/long range. Within each group, the manufacturers generated designs based on 30 ¢/gal fuel, 60 ¢/gal fuel, and minimum fuel. Differences among these designs were rather slight, and only to 30 ¢/gal fuel airplanes were simulated.

Of the three new near-term designs, the 200-seat long-range airplane was dropped because of its noncompetitive economic performance. As shown in Figs. 11 to 13, the N80-200L offers no advantage over baseline or the N80-200I aircraft. Therefore, the simulation involved one intermediate- and one long-range design, each with a good seating capacity for the late-1980 time period and beyond. The resulting simulation is summarized in Table XVIII as Option V.

The favorable economics of the newly designed N80-200I and N80-400L airplanes result in significant fare reduction and demand stimulation. Therefore, the fuel savings achieved are greater on an adjusted than on an actual basis. Although the real impact of these airplanes is not felt until large numbers have been introduced into the fleet, the adjusted annual savings are

already significant by 1985. By 2000, the adjusted savings are over 20 percent, and 60 percent of the fleet consists of these new airplanes.

There is a close parallel between Option IVa, the first derivative case, and Option V. In both instances, a large, fuel-efficient airplane displaces existing wide bodies, thereby saving a large quantity of fuel, but leaving the system otherwise unchanged. The new near-term airplane option saves somewhat more fuel, but also incurs a greater penalty in required fleet investment.

It is important to realize that both the L-1011L and the N80-400L offer significant advantages over the B-747 at short stage lengths (see Fig. 11). As explained in the baseline option, future growth on short, dense routes demands use of large-capacity aircraft, of which the B-747 is most notable among the in-production models. However, the B-747 is quite fuel inefficient at short stages, as indicated in Fig. 11. Therefore, considerable fuel savings over the baseline case are to be expected when the B-747 is replaced by airplanes like the L-1011L or the N80-400L.

New Far-Term Aircraft Options

Advanced technology, beyond the present state of the art as represented by the 1980 aircraft designs, makes possible some important fuel-conserving design features, primarily in the extensive use of composite materials to reduce airframe weight, stability augmentation to reduce drag, and in the improved fuel consumption characteristics of advanced-technology engines, particularly the prop-fan (Ref. 11). Balanced against reliance on these high-technology features to conserve fuel is the fact that their incorporation in production aircraft is a far-term solution; i.e., such airplanes are not likely to be available for service until the late 1980's.

Altogether, four new aircraft designs were considered in the far-term fuel-conservation options. These included one propfan-powered airplane, the N85-200P, which is a 200 seat intermediate-range airplane, synthesized by Lockheed, and three turbofan-powered airplanes. As described in Appendix B, the turbofan designs were adapted from a Boeing study (Ref. 9) of terminal area compatible aircraft. Three far-term aircraft sizes were described: 200-, 350-, and 500-seat versions. In Table IV they are designated N85-200, N85-350, and N85-500. The characteristics of the 350-seat airplane were such that it did not provide an economic advantage over the B-747-200; therefore, only the 200- and 500-seat designs were retained.

Four far-term fuel-conservation options were constructed around these airplanes. The first two feature the N85-200P, introduced either in 1985 (Option VIa) or in 1990 (Option VIb). The nominal introduction period for the far-term aircraft was the mid-1980's, meaning that the first forecast year in which significant numbers could be in service would be 1990. Option VIa was included to test the effect of accelerated R&D on the prop-fan, which might result in a pre-1985 service entry for the N85-200P.

The third far-term option, designated Option VIc, is based on the two turbofan-powered airplanes entering service in the late 1980's. Option VId is similar to VIc except that the N85-200 airplane is replaced by the N85-200P. Although these aircraft have the same seating capacity, the former has a much longer maximum stage length (Table IV), while the latter is more fuel-efficient at short- and intermediate-stages (Figs. 11 and 12). Thus, although only one propeller-driven airplane was provided in the study, it appears in three of the four far-term aircraft options.

Considering the prop-fan options first, the summaries in Table XIX show that early introduction of the N85-200P does have a noticeable impact. The early start in building the N85-200P fleet results in a considerable difference in fuel saved between Options VIa and IVb. In both cases, the baseline airplanes replaced by the N85-200P are the B-727-200 and DC-10/L-1011; larger and smaller baseline airplanes are virtually unaffected.

Fuel savings in Options VIc and VId are considerably greater than in the first two cases. However, this is to be expected because these options involve two new far-term aircraft while the first two options involve only one. Futhermore, the fuel saving advantage of replacing the B-747 with the N85-500 is considerably greater than the corresponding saving associated with replacing other baseline aircraft with the N85-200 and N85-200P. As in the derivative and new near-term aircraft options, much of the fuel savings can be traced to replacement of the B-747 with more fuel-efficient designs, particularly on short, dense routes which require a large-capacity airplane.

The annual fuel savings achieved in Options VIc and VId become quite large by the year 2000 when almost half the fleet consists of the new far-term airplanes. Although the saving in cumulative fuel used in these two cases does not really take effect until after 1990, the saving in the last decade of the 27-year forecast period is very large, resulting in a 10.6 percent adjusted saving in fuel over the baseline in both cases. As observed in other options, this latter period tends to dominate cumulative statistics because demand levels are significantly higher than in the early periods -- a consequence of accumulated growth in demand (and, therefore, fuel used) throughout the forecast period.

TABLE XIX

NEW FAR-TERM AIRCRAFT OPTIONS
RECAT 600 CITY-PAIR NETWORK

	1973	1980	1985		1990					2000				
		Baseline	Baseline	Turboprop (VIa)	Baseline	Turboprop (VIa)	Turboprop (VIb)	Turbofan (VIc)	Turbofan & Turboprop (VId)	Baseline	Turboprop (VIa)	Turboprop (VIb)	Turbofan (VIc)	Turbofan & Turboprop (VId)
Enplaned Pass.-Miles (10^9)	107.50	168.83	224.14	223.42	280.45	281.15	281.36	285.20	284.26	436.13	436.31	436.44	447.95	447.05
Fuel: Total (10^9 gals)	5.808	6.656	8.440	8.165	10.536	9.955	10.193	9.649	9.620	16.400	15.386	15.417	12.168	12.168
Savings vs Baseline: (%)														
Actual	-	-	-	3.3	-	5.5	3.3	8.4	8.7	-	6.2	6.0	25.8	25.8
Adjusted	-	-	-	2.9	-	5.7	3.6	10.0	9.9	-	6.2	6.1	27.8	27.6
Efficiency: Pass-mi/gal	18.51	25.37	26.56	27.36	26.62	28.24	27.60	29.56	29.55	26.59	28.36	28.31	36.81	36.74
Seat-mi/gal	36.15	45.53	46.32	47.78	46.17	48.75	47.70	50.95	51.05	45.86	48.82	48.74	63.38	63.27
Improvement vs Baseline	-	-	-	3.2	-	5.6	3.3	10.4	10.6	-	6.5	6.3	38.2	38.0
Fares Relative to 1973	1.000	0.995	0.957	0.958	0.950	0.947	0.947	0.934	0.935	0.937	0.935	0.935	0.897	0.899
Load Factor (%)	51.2	55.7	57.3	57.3	57.7	57.9	57.8	58.0	57.9	58.0	58.1	58.1	58.1	58.0
Flights/Day	6615	7328	8240	8239	8959	8945	9019	8990	8964	11,103	10,984	11,054	10,517	10,543
Average Capacity - Seats/Flight	136	172	192	193	209	211	209	212	214	249	256	255	275	273
Fleet Size: Total	1372	1549	1771	1767	1992	1978	1996	1995	1981	2551	2511	2524	2428	2430
B-747	65	113	227	214	353	351	356	244	244	840	868	869	253	256
DC-10/L1011	100	240	340	306	455	334	357	324	365	651	389	380	314	397
B-727-200	247	619	845	765	955	773	361	840	849	956	601	626	546	620
B-737-200/DC-9-30	259	368	360	359	228	227	231	231	231	110	106	108	105	104
Other[1]	701	209	0	0	0	0	0	0	0	0	0	0	0	0
N85-200P	-	-	-	[illegible]	-	292	191	-	201	-	546	540	-	549
N85-200	-	-	-	-		-	-	265	-	-	-	-	695	-
N85-500	-	-	-	-	-	-	-	92	92	-	-	-	515	504
New Aircraft Investment: (10^9\$)														
Since Previous Forecast	12.749	7.932	7.836	8.171	13.577	14.385	14.414	14.803	14.673	30.256	31.375	31.362	32.021	31.831
Cumulative 1973 Present Value (8% Discount)	-	5.900	9.551	9.707	13.951	14.268	13.122	14.245	14.204	19.436	19.956	19.808	20.050	19.975

[1] DC-8, DC-9-10, B-707, B-720, B-727-100, CV-880, Turboprops

Finally, it is noted that the new aircraft investments for the new far-term aircraft options are only marginally greater than for the baseline case, because the differences in aircraft price per seat (Table IV) and fleet size (Table XIX) tend to compensate. Thus, the fuel savings in Table XIX are achieved without appreciable increments in investment over the baseline case.

Comments on Propfan

It is clear from the results of the far-term options that it has not been possible to treat propfan-powered airplanes fairly in this study. To a large extent this is an unfortunate consequence of the lack of consistent assumptions in defining near-term and far-term technologies, which is in turn due to the lack of adequate propfan data at the start of the study. This technology is only now emerging in terms of credible performance information.

The results of Option VI may appear to conflict with Figs. 11 and 12 which show the N85-200P to compare favorably with the N85-200 in fuel efficiency. Moreover, the better fuel efficiency of the N85-200P occurs in spite of the fact that it does not benefit as much from advanced airframe design (use of composite materials) as the N85-200. However, the N85-200 also has the advantage of a much greater range (see Table IV), thereby permitting it to compete on many more routes. For this reason its impact was greater, although the differences between Options VIc and VId, from which the impacts of these airplanes can be compared directly, is quite small.

As noted earlier, the lack of a large-capacity airplane with propfan power is a major impediment to Options VIa and VIb. On this basis alone, a comparison of results among the far-term aircraft options, or between the propfan cases and other options, is not valid. In this regard, it might be argued that, on the basis of comparable airframe technology, Option VIc might better be compared with Option V. However, lack of a large-capacity propfan-powered design precludes a fair comparison even in this case.

Therefore, it appears that further analysis is required to determine the true potential of the propfan as an alternative to the turbofan. In view of the attractive fuel efficiency of the N85-200P, it is probable that this potential is significant if properly exploited. An example of this potential was explored in an approximate manner; results are given on pg. 150.

Fuel Savings from Large-Capicity Aircraft

For many of the options where large savings in fuel are shown, one of the most important factors has been the replacement of the B-747 on short routes where that airplane is not fuel-efficient. In view of the major role this changeover assumes in the study, it is important to understand how it comes about.

Of paramount importance is the study assumption concerning the future capacities of major hub airports. Data supplied by UAL for ten major hub airports suggested only about a 25 percent expected increase in overall capacity for air carrier movements over 1973 (Refs. 2, 13). The implication of this estimate is that an increase in demand of more than 25 percent can be accommodated only by an increase in average seating capacity of aircraft if extreme congestion is to be avoided. Even if this estimate is conservative, very large increases in capacity will be required to handle the demand growth forecasted out to the year 2000.

Using the estimate provided by UAL as a guideline, the frequency rules described earlier were conceived to restrain growth in air carrier movements, particularly on the densest routes which invariably involve one or more major hub airports. In general, on high-density routes (greater than 16 daily flights) frequency is allowed to decrease slightly but may not increase, and on low-density routes frequency may not decrease but can increase. The result is that the aircraft assignment algorithm tends to favor large airplanes on dense routes and small airplanes on lightly traveled routes.

Many of the densest routes are of relatively short stage length. For example, Table XX summarizes some baseline data for the busiest city-pairs (ranked by frequency) in the study, showing that only one route was greater than 1000 miles. The average stage length of these ten city-pairs, weighted for 1973 frequency, is only 335 miles. The table also shows that there is an almost fourfold growth in demand during the 27-year forecast period. Obviously, much of this growth must be accommodated by increases in seating capacity.

The result was assignment of the B-747 to many short-haul routes in the baseline case. On some important routes, namely short stages involving New York or Washington, D.C., the B-747 is ruled out because of limitations at LaGuardia and National Airports. This means that frequencies on some other routes must be further constrained to avoid congestion, resulting in even more extensive use of wide bodies like the B-747.

An important implication of the use of the B-747 at short stage lengths is its poor fuel efficiency over these stage lengths (Fig. 11). As has been pointed out, this means that the more fuel-efficient large aircraft achieve a large fuel saving when assigned to replace the B-747. It is important that the ten busy city-pairs in Table XX accounted for 10% of the fuel used in the 600 city-pair system. The list would have been different if the ranking had been based on fuel used rather than frequency; in particular, the average stage length would be much longer (1700 mi) and the amount of fuel used would be 18% of the total system fuel. However, the advantage to be gained in fuel efficiency at these long stage lengths by introducing new aircraft is not as great as it is at short stages because existing wide bodies are already quite fuel-efficient on long-distance routes. Nevertheless, even a small percentage improvement will permit a substantial fuel saving. Two significant conclusions can be formulated on the basis of these results: 1) the greatest fuel savings are achieved by large airplanes operating on high-volume routes, and 2) a large airplane with good fuel efficiency at short stage lengths can have a great impact on fuel savings.

TABLE XX

SUMMARY OF OPERATIONS FOR TOP 10 CITY-PAIRS

(Based on 1973 Flights/Day)

	1973				2000			
	Distance St mi	Flights*	Passengers*	Dominant Airplane (% of Flights)	Flights*	Passengers*	Dominant Airplane (% of Flights)	Airplane Assigned
Los Angeles - San Francisco	335	129.2	10,103	3 ENB(46)	165.6	35,917	4 EWB(90)	4 EWB
New York - Washington	206	64.0	3,408	2 ENB(52)	77.6	12,138	3 EWB(90)	3 EWB
New York - Boston	182	60.5	3,496	2 ENB(47)	74.3	11,483	3 EWB(89)	3 EWB
New York - Chicago	712	58.6	3,573	3 ENB(62)	67.3	10,217	3 EWB(85)	3 EWB
Los Angeles - San Diego	103	58.5	3,388	3 ENB(43)	70.4	14,803	4 EWB(81)	4 EWB
Seattle - Portland	138	38.3	1,518	3 ENB(49)	30.5	5,868	4 EWB(56)	4 EWB
Dallas - Houston	228	37.4	2,088	3 ENB(52)	42.3	9,283	4 EWB(87)	4 EWB
Los Angeles - Las Vegas	219	36.9	2,048	2 ENB(67)	52.2	11,756	4 EWB(96)	4 EWB
New York - Miami	1100	33.0	2,516	3 ENB(53)	52.0	10,645	4 EWB(88)	4 EWB
New York - Pittsburg	316	30.4	1,366	2 ENB(53)	29.6	4,361	3 EWB(81)	3 EWB
TOTAL	335(Avg.)	546.8	33,504		661.8	126,471		
Fraction of 600 City-Pairs		16.5%	16.6%		11.9%	15.6%		
Increase from 1973: 10 city pairs		---	---		21.0%	277.5%		
600 city pairs		---	---		67.8%	302.8%		
Pass./Flight: 10 city-pairs		61.3			191.1			
600 city pairs		61.1			146.5			

* Daily in each direction

IMPACTS ANALYSIS

Although the technology options considered in this study have fuel conservation as the major objective, each option can be expected to impact the various sectors of the air transport industry in other ways as well. In this section the impacts of each technology option are considered with respect to airlines, manufacturers, airports, and government. The impacts are analyzed by isolating particular parameters which affect each sector, where the following list shows the parameters used in each case.

Sector	Impact Parameter
Airlines	Annual Enplaned Passenger-Miles Undepreciated Fleet Value Fleet Seating Capacity
Manufacturers	Annual Aircraft Deliveries Annual Value of Deliveries
Airports	Annual Airport Activity Hub Capacity Used Noise Exposure
Government	Annual Fuel Used Annual Emissions Cumulative Spending
Air Traveler	Fare Service (Enplaned Passenger Miles)

The impacts are considered in the short term and in the long term, 1985 being used to represent short-term impacts and 2000 for the long-term impacts. All results are presented as percentage differences relative to the baseline case; i.e., the impact measured is the percent change of each parameter relative to the baseline value. As a convenience in identifying the options, Table XXI summarizes all the cases considered in this study, including option designations and names, and the aircraft available for assignment in each case. This table will be a useful reference in this section as well as in succeeding sections.

Airline Impacts

Impacts on the airlines are given in Figs. 23 to 25; each chart summarizes the comparisons of one impact measure over all technology options for each of the two years. The first parameter, annual enplaned passenger-miles, is a measure of the volume of airline business. Therefore, positive differences indicate an increase in airline business activity compared to baseline values.

TABLE XXI

KEY 1 UTRC FUEL-CONSERVATION OPTIONS

	Option	Aircraft Available for Assignment
Ia	Baseline Baseline Sensitivities	Baseline In-Prod. Models* (BIPM)
	60¢/gal Fuel	BIFM
Ib	Fuel Allocation LF = 70%	"
IIa	Operating Procedures: Present ATC	BIPM
IIb	" " : Advanced ATC	"
$IIIa_0$	Retro/Mod: In-Prod. only	BIPM
$IIIa_1$	" " : Aero; Proj. Ret'm'ts.	"
$IIIb_1$	" " : Aero + Eng; Proj. Ret'm'ts.	"
$IIIa_2$	" " : Aero; Delayed Ret'm'ts.	"
$IIIb_2$	" " : Aero + Eng; Delayed Ret'm'ts.	"
IVa	Basic Derivative Option	BIPM +: DC-9-30D1;DC-10-10D;L1011L
IVb	Without L-1011L	" + " "
V	New Near-Term Aircraft	BIPM +: N80-200I; N80-400L
VIa	New Far-Term TP: Pre-1985 Intro.	BIPM +: N85-200P
VIb	" " " ": 1985 Intro.	" ": N85-200P
VIc	" " " TFs	" ": N85-200; N85-500
VId	" " " TP + TF	" ": N85-200P; N85-500
VIe	" " " TPs (estimate)	" ": N85-200P; N85-500P (est)

* DC-9-30; B-737; DC-10/L1011; B-747-200; B-727-200

AIRLINE IMPACT

ANNUAL ENPLANED PASSENGER–MILES RELATIVE TO BASELINE

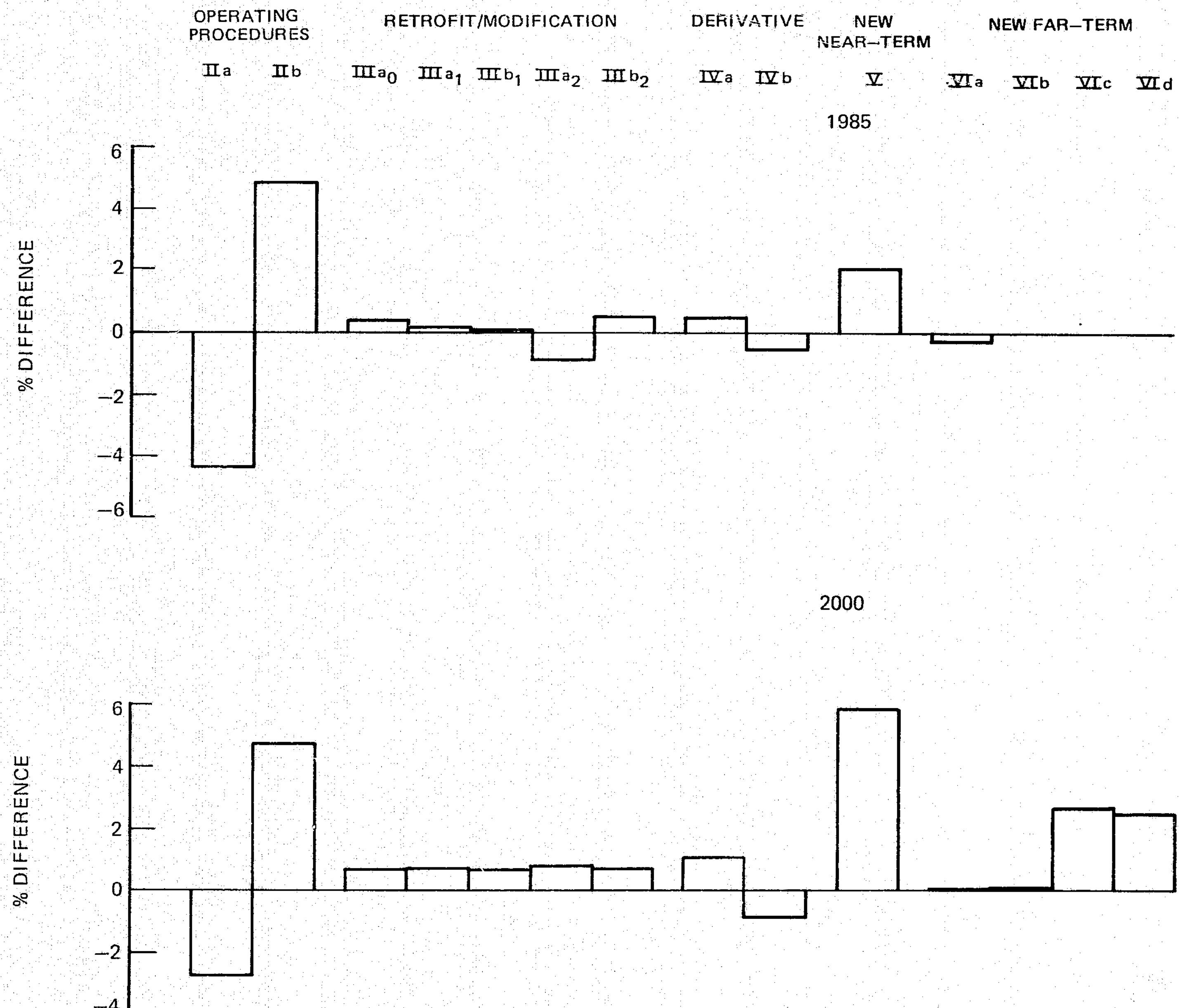

FIG. 23

R76–912036–16

AIRLINE IMPACT

UNDEPRECIATED FLEET VALUE RELATIVE TO BASELINE

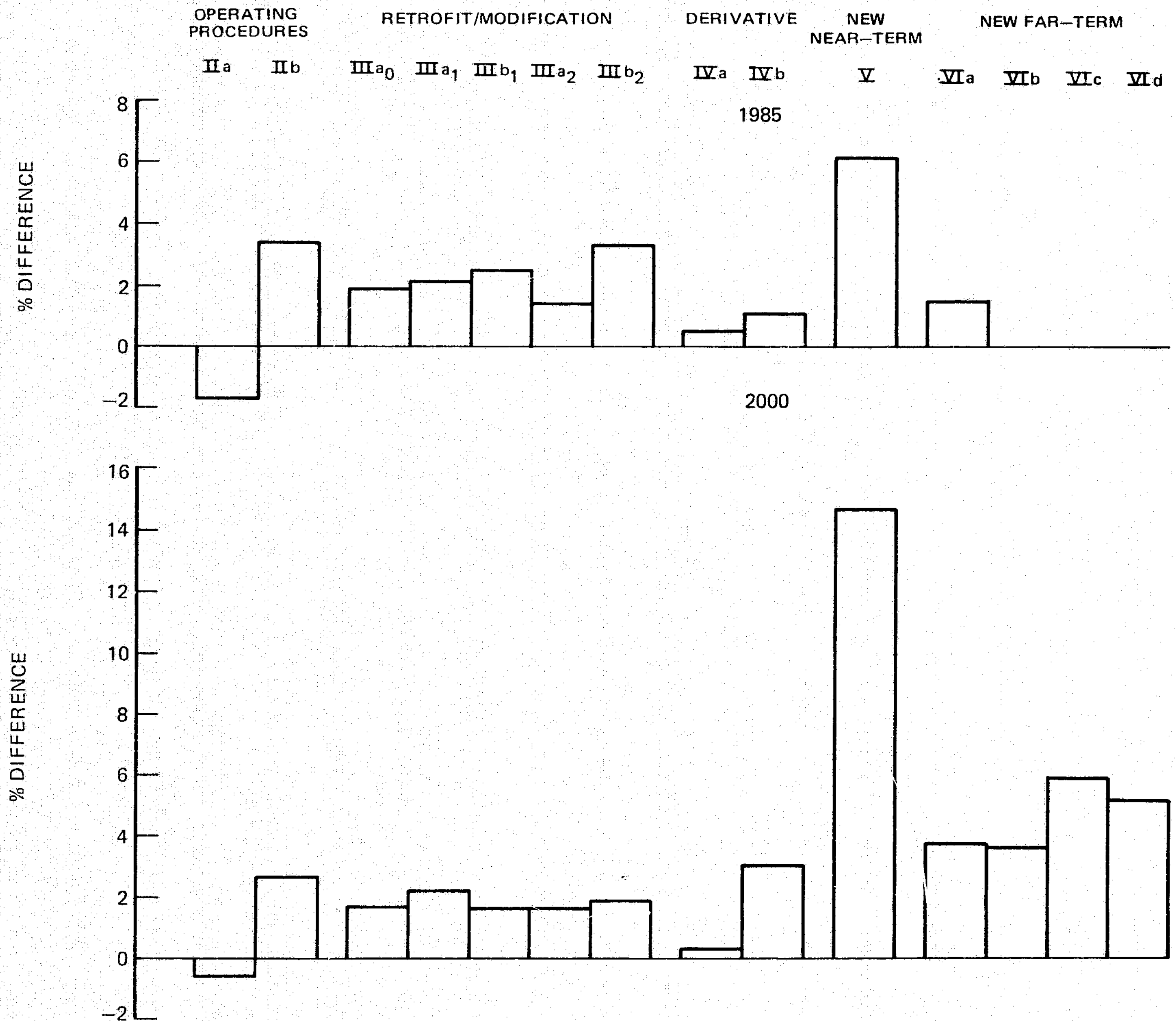

FIG. 24

76–03–71–18

AIRLINE IMPACT

FLEET SEATING CAPACITY RELATIVE TO BASELINE

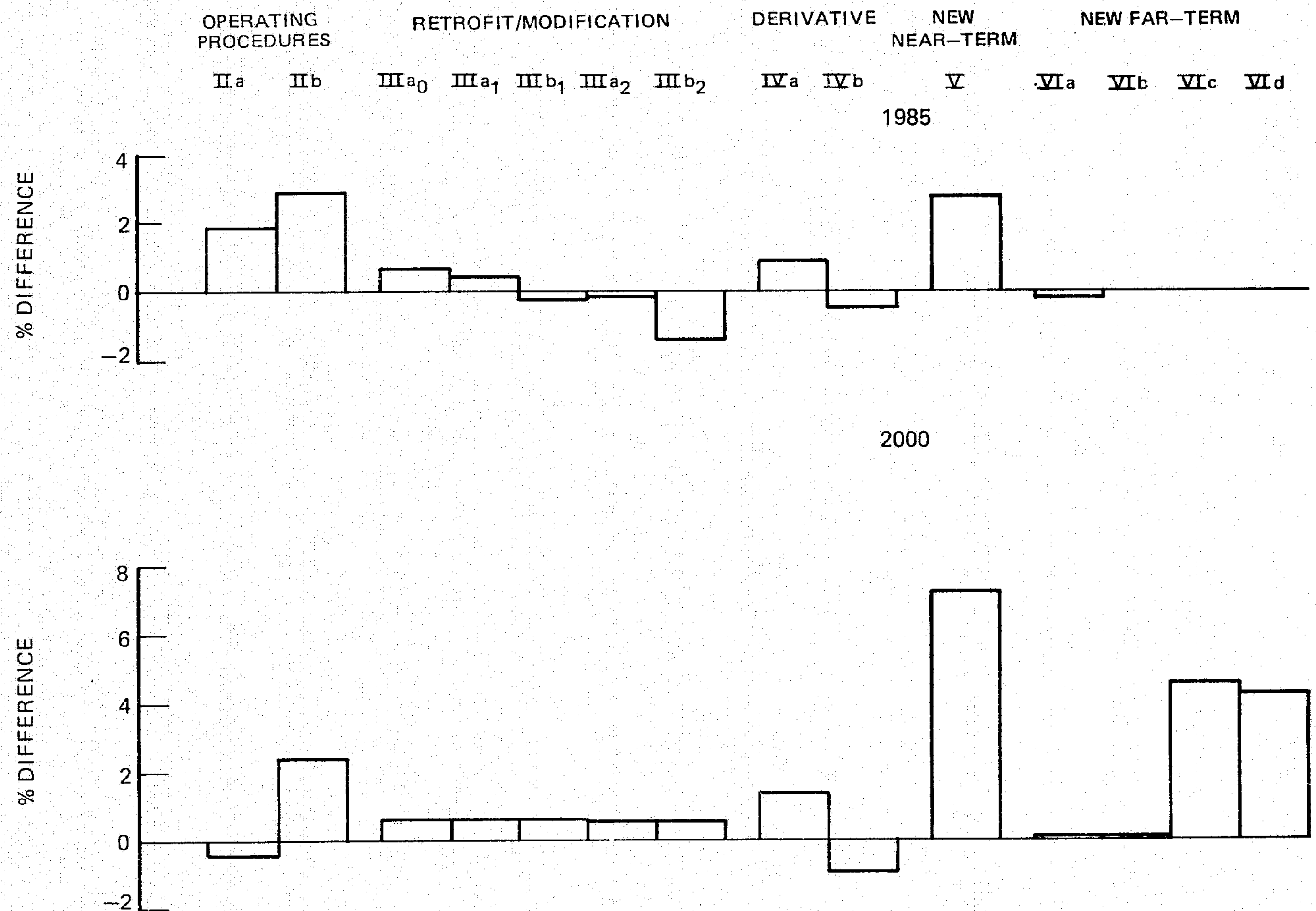

FIG. 25

The second parameter, undepreciated fleet value, is a crude measure of the amount of capital invested in the fleet. Ideally, the effect of depreciation should be included, but the assumptions which must be made and the complexity of the computation to include the depreciation effect were considered to be unnecessary complications. Fleet seating capacity, the third parameter, is a measure of the total capacity of the fleet required to meet the forecasted demand.

In general, it would be expected that fleet investment and capacity would follow demand; i.e., an increase in demand, relative to the baseline, should require more seats and a greater investment in the fleet. However, aircraft size and cost per seat are also important variables among the different options. Particularly in the short term, the correspondence between demand and fleet investment is seen to be rather weak.

From the airlines' point of view, increases in demand are desirable, but not if they are accompanied by large increases in required investment. Comparing the options on this basis, it is apparent that Options IIb and IVa are especially good because the airline investments in each case are in line with the demand increases achieved. The worst case is Option IVb which requires greater than the baseline investment in spite of lower demand in both time periods. Overall, the results show that the most desirable short-term airline effects occur in Option IIb because, in this case, the system in which the airlines operate presently available equipment is improved.* In the long term, Option IIb is still good but Option IVa may be even better because of the very small required investment for derivative aircraft.

Manufacturer Impacts

The manufacturer impacts, stated in terms of annual aircraft deliveries and value of deliveries, are given in Figs. 26 and 27. These figures show that from the standpoint of the manufacturer, the retrofit/mod options are especially unattractive in the short term because deliveries of new aircraft are delayed when lifetimes of older aircraft are extended. Even though the value of the retrofit/mod business is included in Fig. 27, the results compare unfavorably with most other options. (It should also be noted that at least some of the retrofit business credited to the manufacturers will be performed by the airlines themselves.) Also, it can be seen that Option IIb is favorable in the short term because system improvements stimulate additional demand, but that it is much less attractive in the long term.

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*Although investments in onboard equipment will be required to take advantage of improved ATC, these investments were neglected in this study.

R76–912036–16

MANUFACTURER IMPACT

AVERAGE ANNUAL AIRCRAFT DELIVERIES RELATIVE TO BASELINE

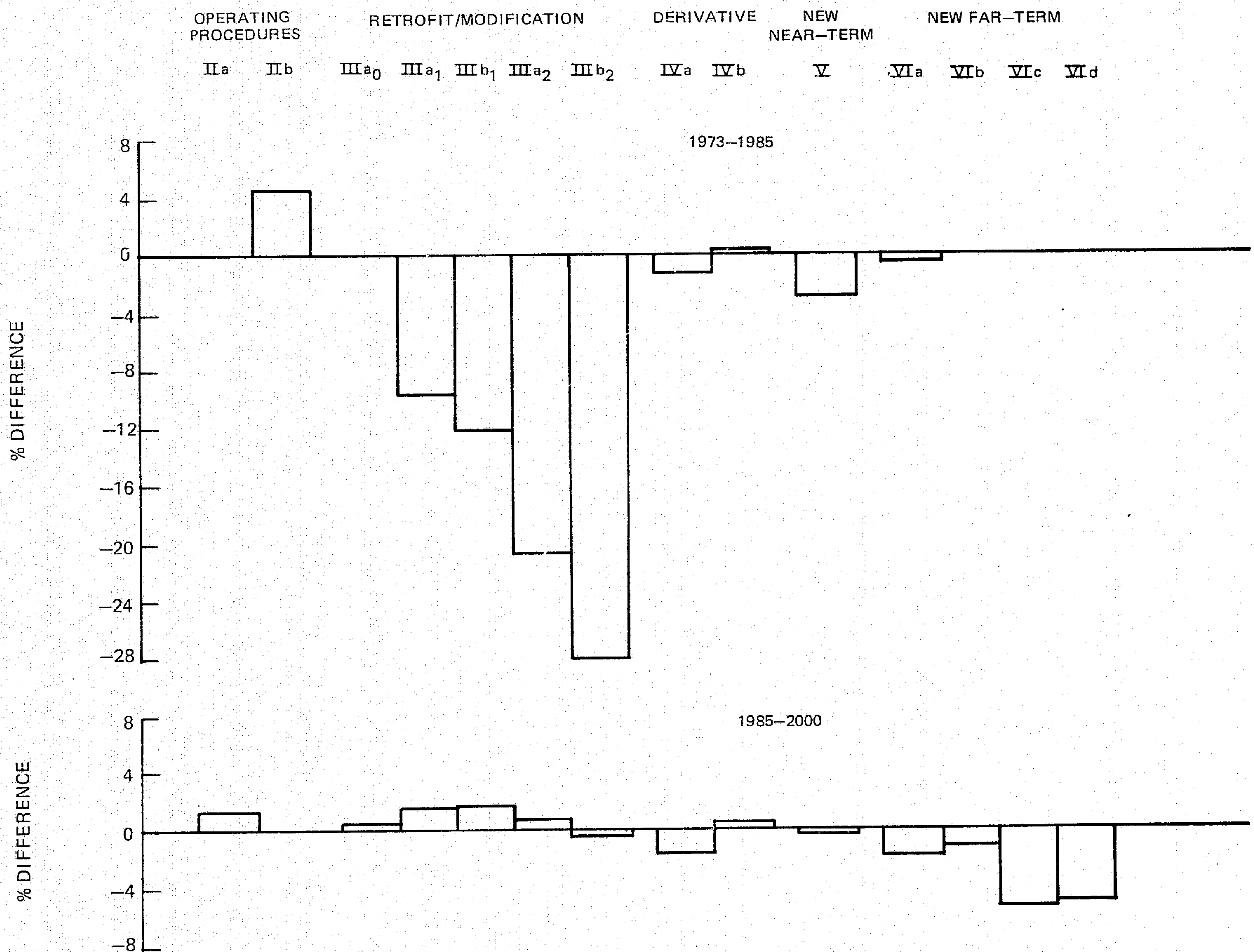

FIG. 26

76–03–71–1

MANUFACTURER IMPACT

AVERAGE ANNUAL VALUE OF AIRCRAFT DELIVERIES RELATIVE TO BASELINE

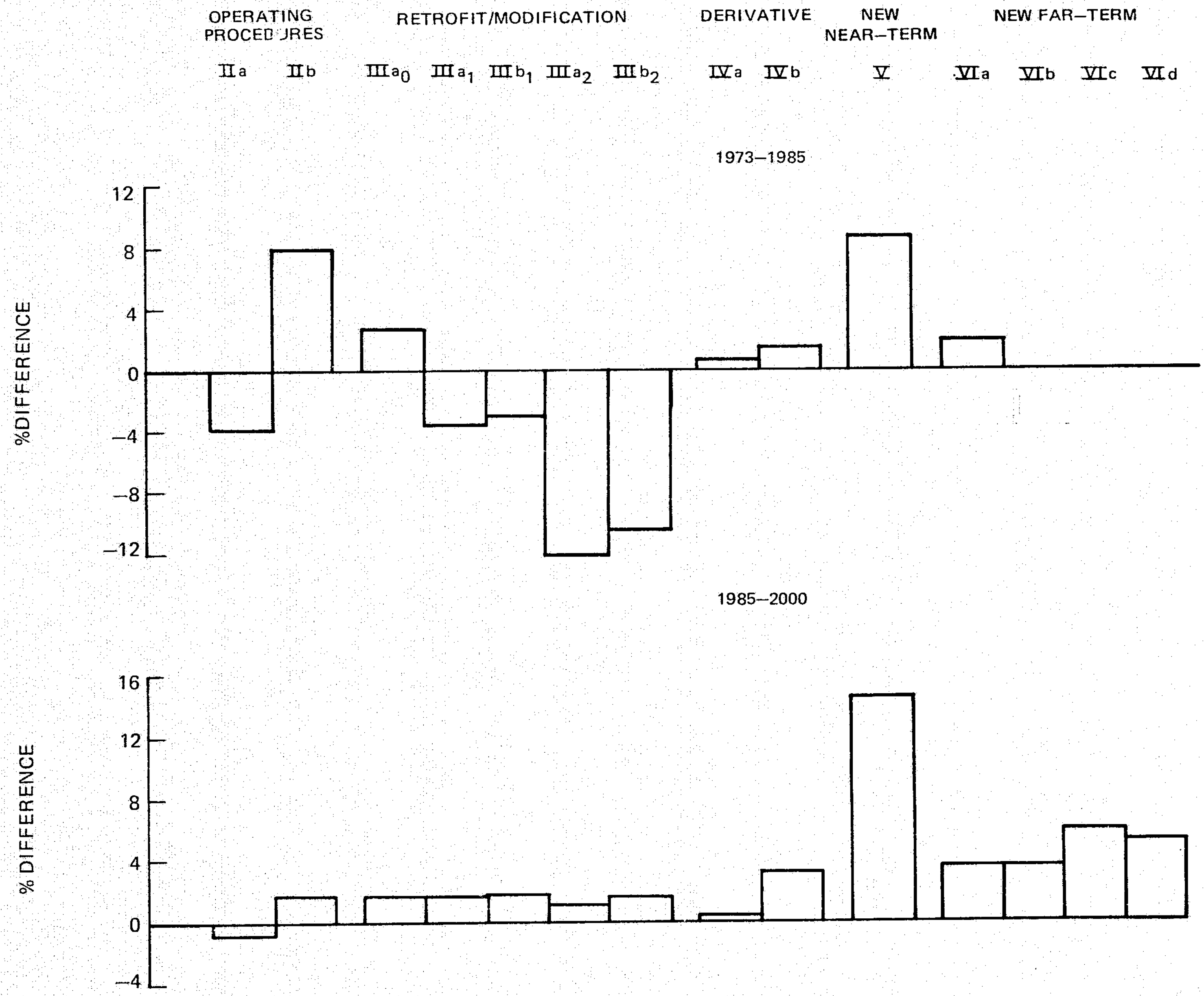

FIG. 27

It is not surprising that the best manufacturer impacts are from the new aircraft options, the new near-term aircraft option (Option V) showing up especially well because these airplanes are relatively expensive in $ per seat. Although smaller numbers of aircraft are produced, compared with the baseline case, because of the aircraft are larger than present models, the value of these airplanes is up substantially. In general, manufacturers appear to benefit more than airlines from the new near-term aircraft option.

Airport Impacts

The next set of impacts, in Figs. 28 to 30, concern the effects on airports. Two considerations drive the results in these figures: 1) the frequency and fleet assignment rules which led to steady increases in average seating capacity, and 2) increasing use of airplanes with quiet engines compared with current narrow-body types.

Since the frequency rules were operative in the baseline case as well as in the technology options, relative airport activity grows much more slowly than demand in all cases. However, because the new-aircraft options featured airplanes of ever-increasing size, airport activity grew still more slowly in these cases. As seen in Fig. 28, significant reductions in activity occur in Options IVa and V, and also in the new far-term options (VI), in the long term. Lower activity is also evident in Option IIa, but this reduction is a consequence of depressed demand. The impact of Option IIb is somewhat deceptive in that it shows higher-than-baseline activity, a consequence of higher demand. However, improved ATC ought to benefit the airports because it reduces delays and because it can augment the favorable impact of the technology options.

Results for the percent changes in hub capacity used, as depicted in Fig. 29, are closely parallel to Fig. 28. However, a notable exception is the improved standing of Option IVa in terms of hub activity. The differences between total system activity (Fig. 28) and activity at hubs (Fig. 29) are a consequence of more concentrated use of large aircraft at the busiest airports. Since the frequency rules were postulated to contain operations growth rates on the densest routes, activity at hub airports grows slower than total activity in the system. Therefore, options featuring the largest aircraft will show up better in Fig. 29 than in Fig. 28, although the basic impact is the same; namely, that airport operations are favorably affected by introduction of large aircraft.*

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*Compensating features of larger airplanes are: accelerated runway deterioration, space requirements at gates and on taxiways, and terminal congestion due to large passenger groupings. Consideration of these additional factors was not attempted in this study.

AIRPORT IMPACT

ANNUAL AIRPORT ACTIVITY RELATIVE TO BASELINE

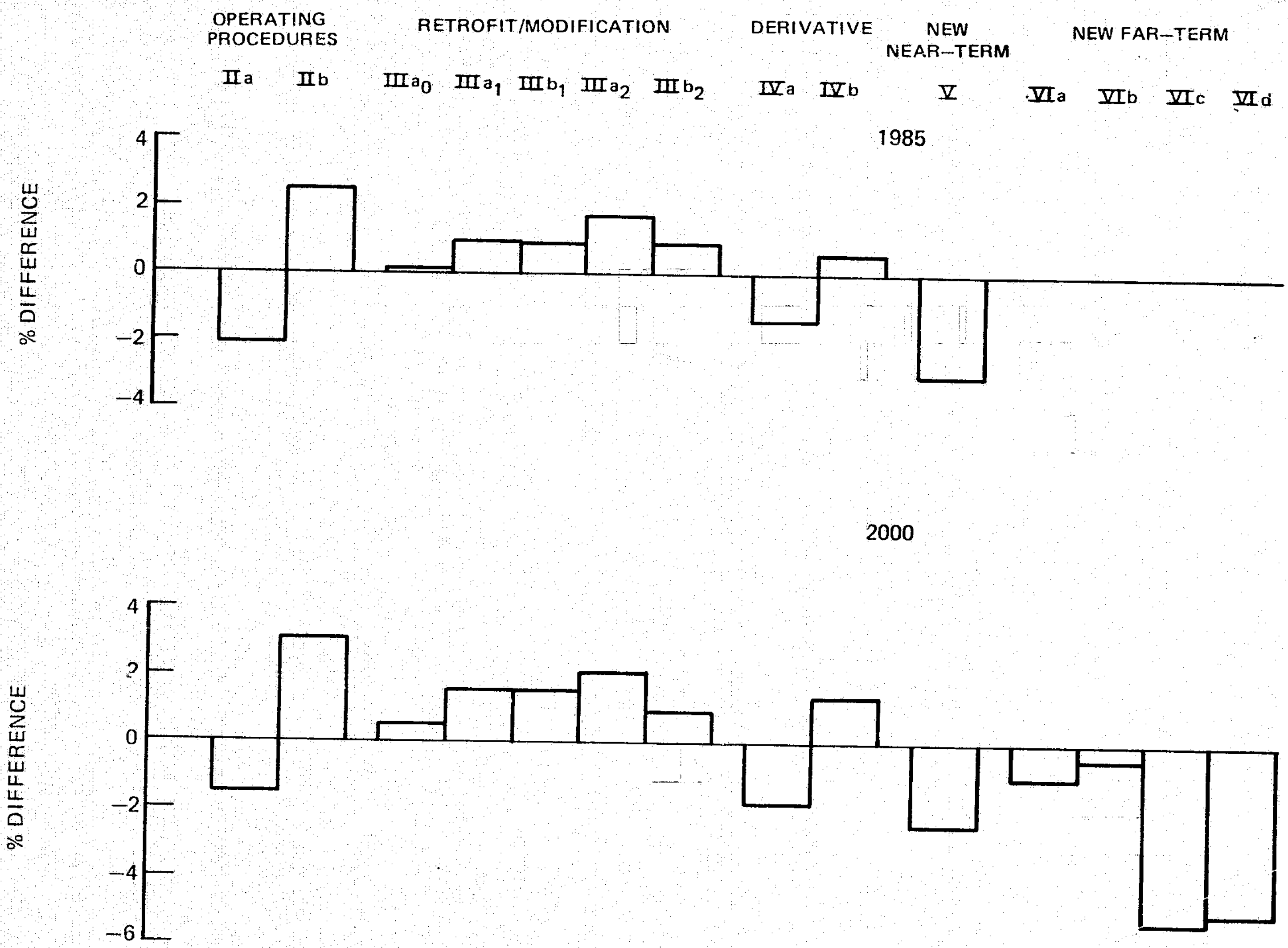

FIG. 28

76–03–71–25

AIRPORT IMPACT

HUB CAPACITY USED RELATIVE TO BASELINE

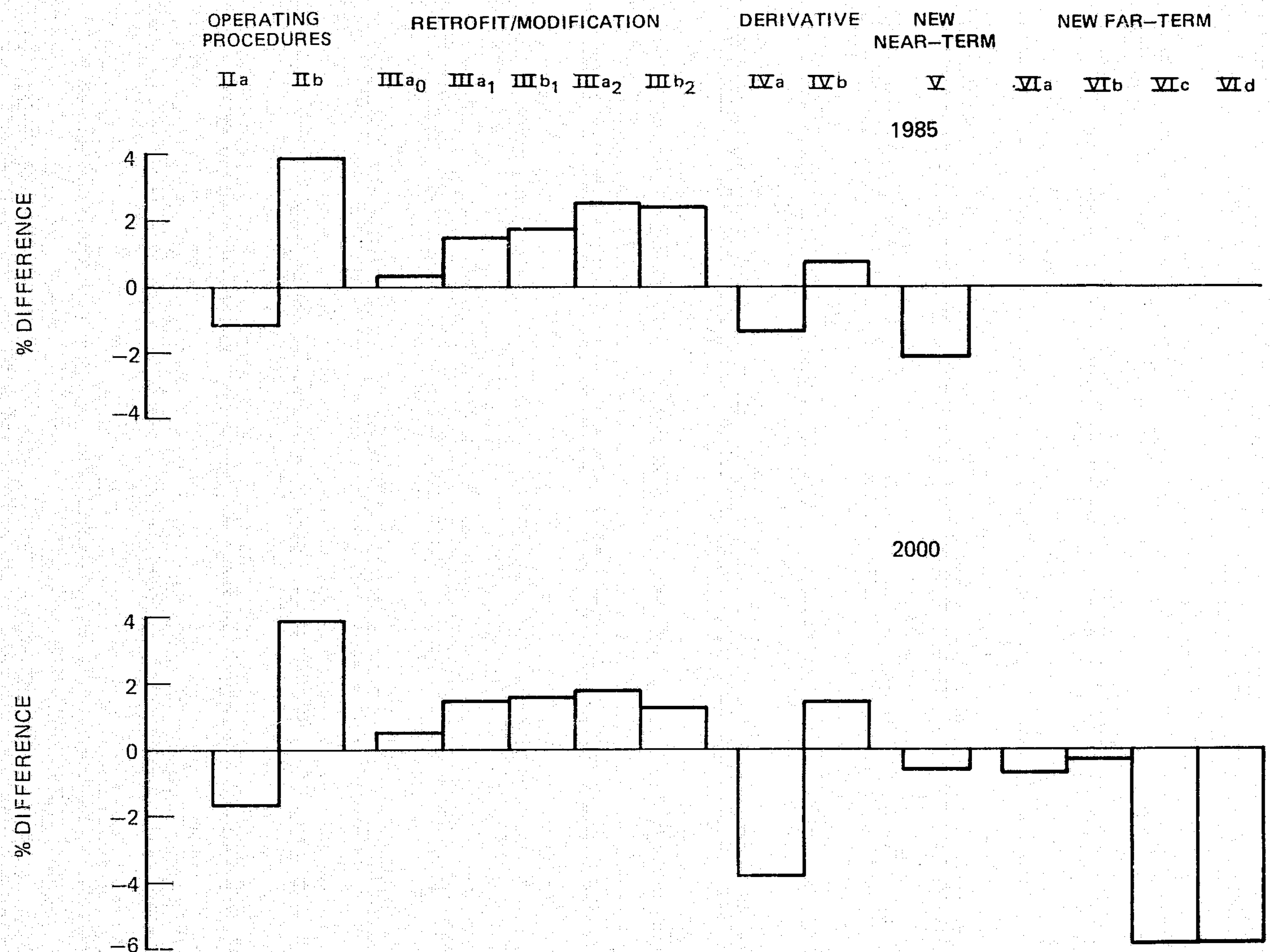

FIG. 29

AIRPORT IMPACT

NOISE EXPOSURE RELATIVE TO BASELINE

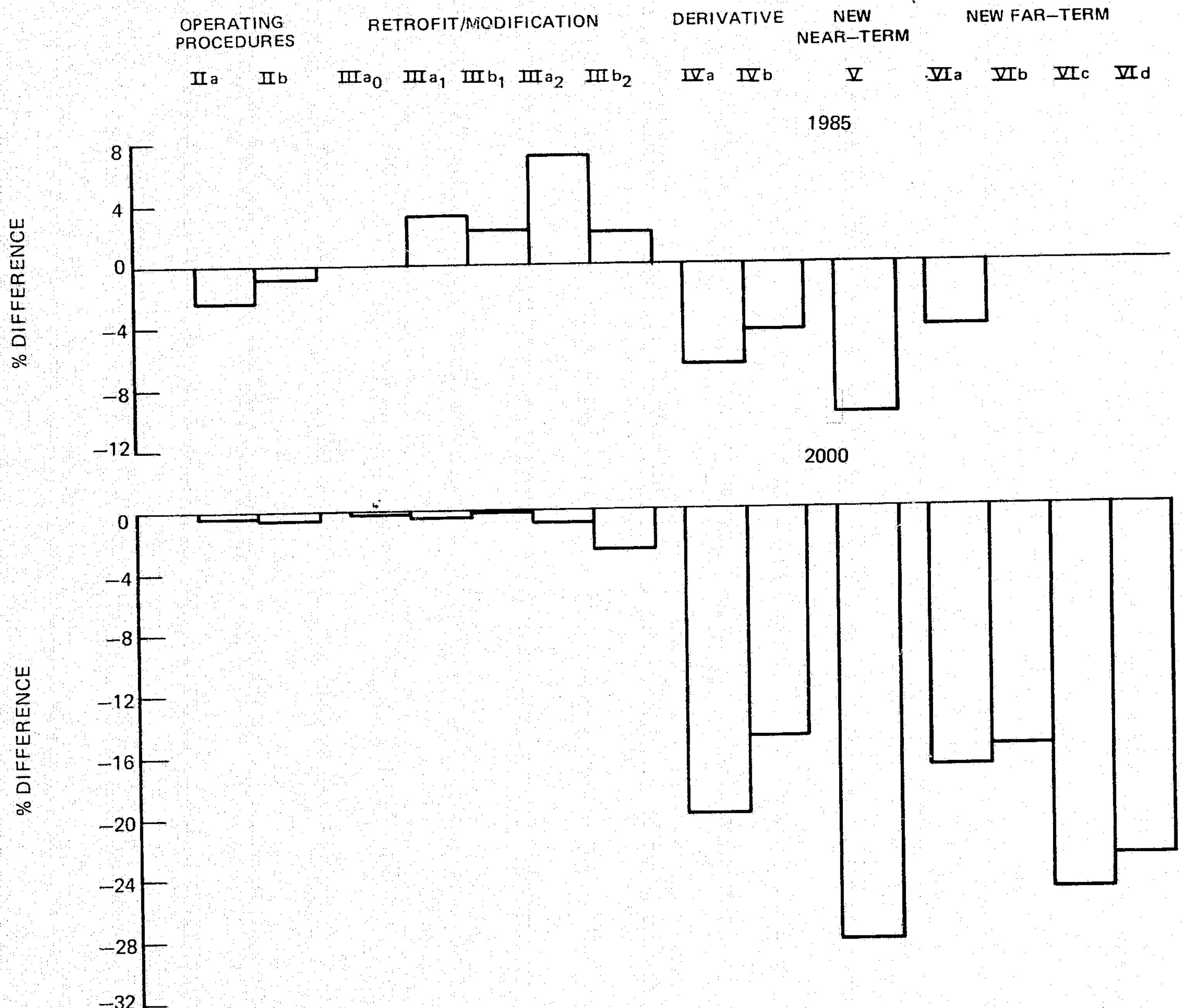

FIG. 30

76–03–71–24

GOVERNMENT IMPACT

ANNUAL FUEL USED RELATIVE TO BASELINE

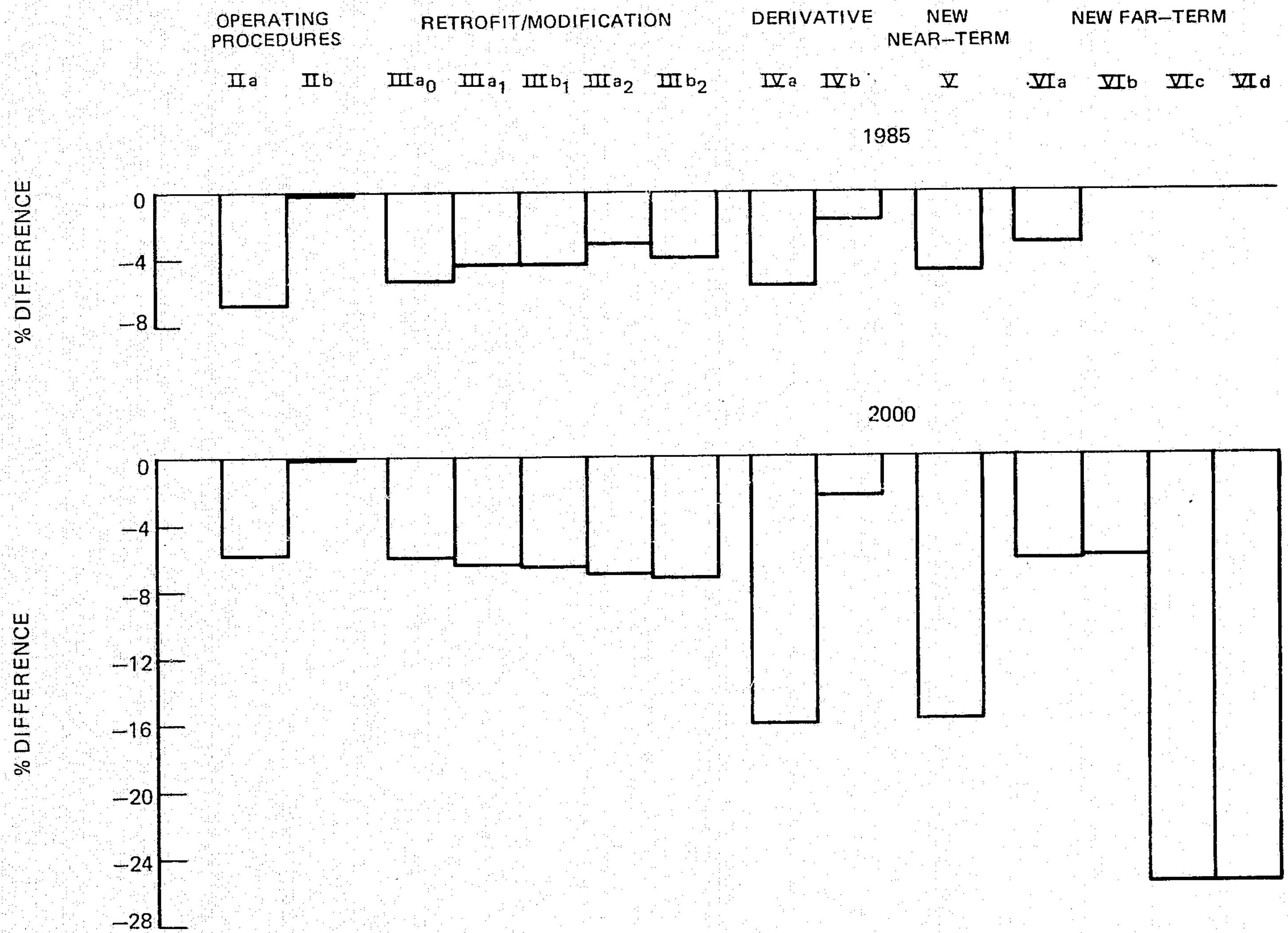

FIG. 31

76–03–71–20

GOVERNMENT IMPACT

ANNUAL EMISSIONS RELATIVE TO BASELINE

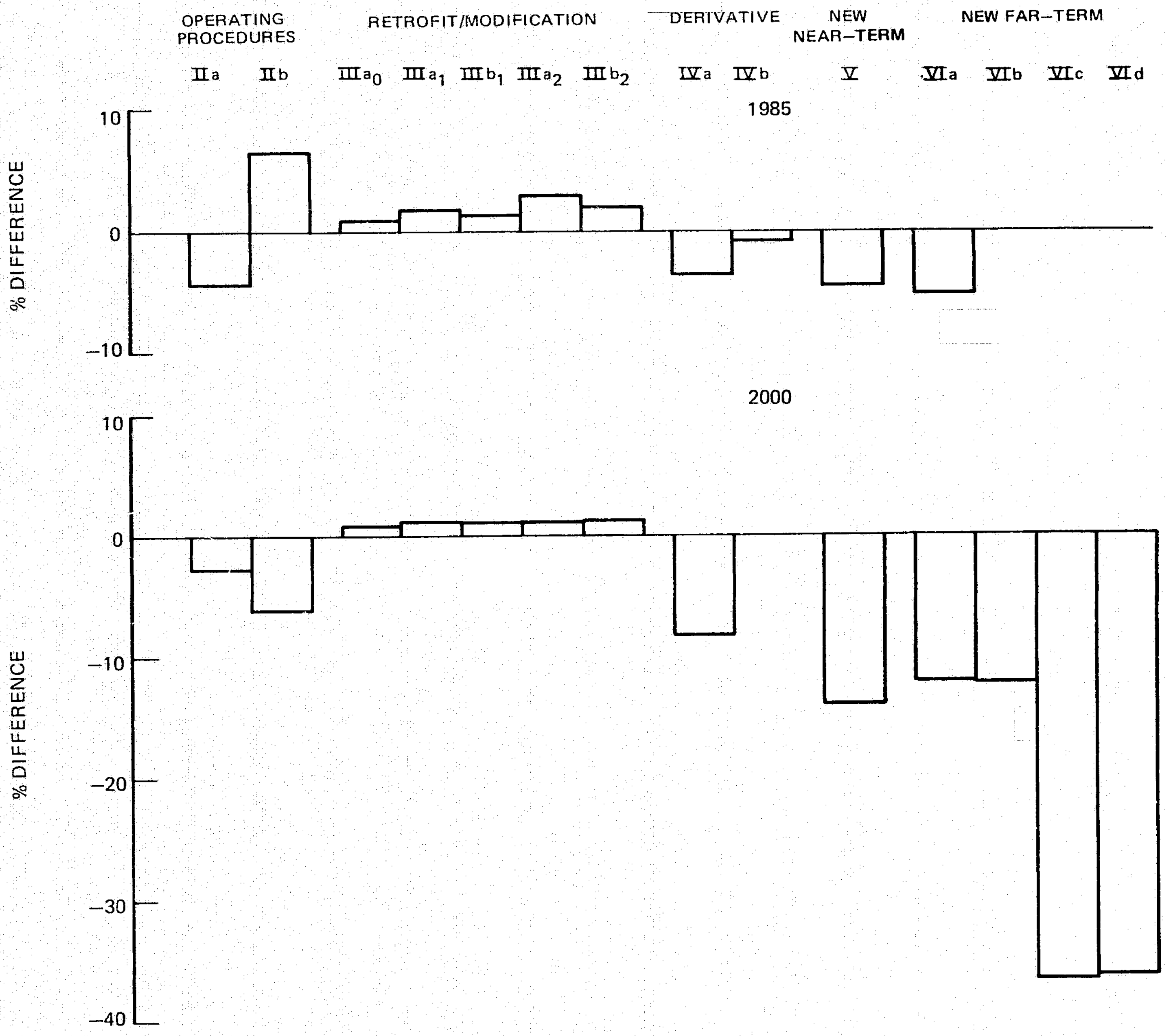

FIG. 32

76-03-71-16

GOVERNMENT IMPACT

CUMULATIVE R&D SPENDING RELATIVE TO BASELINE

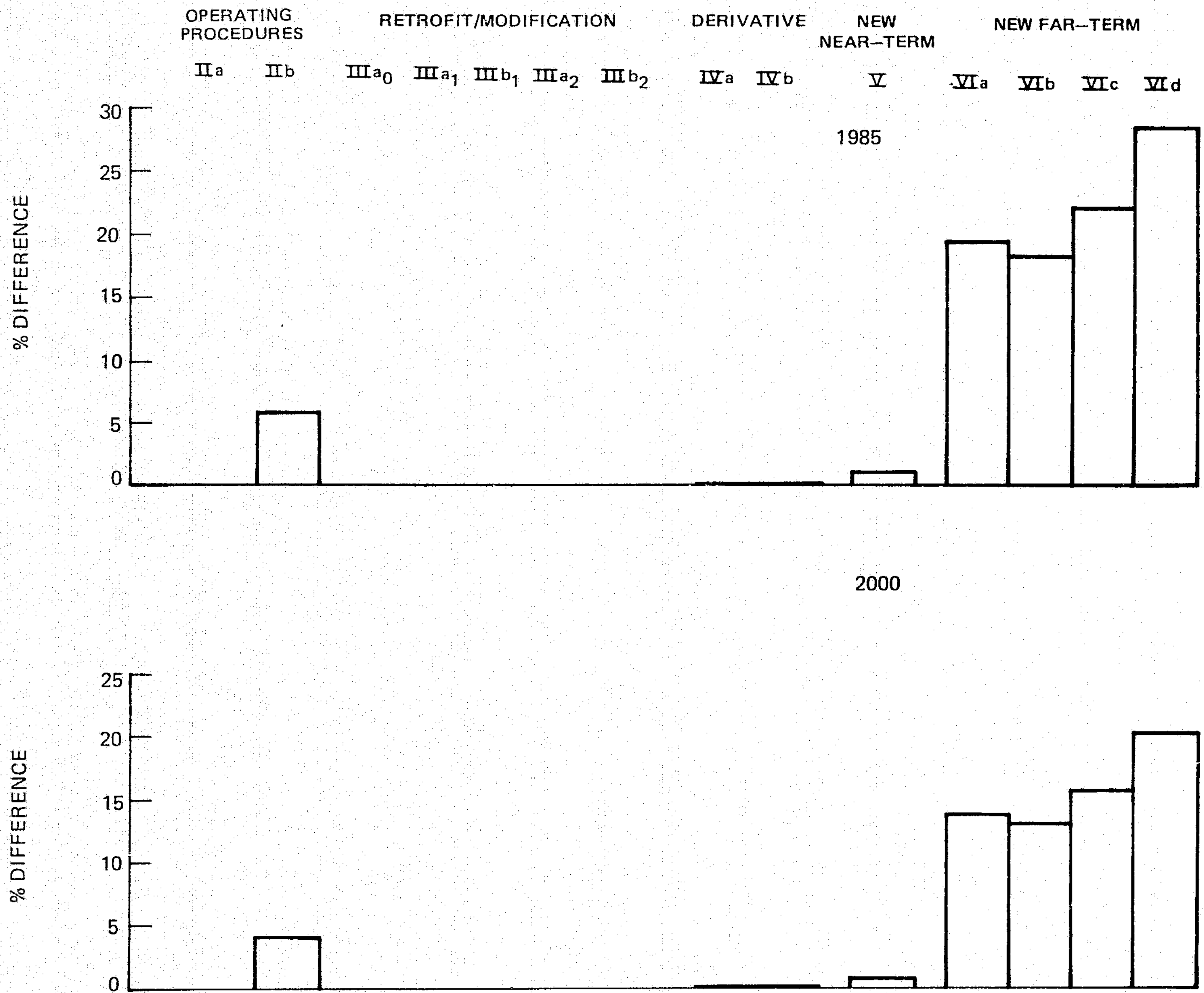

FIG. 33

76–03–71–17

AIR TRAVELER IMPACT

FARE RELATIVE TO BASELINE

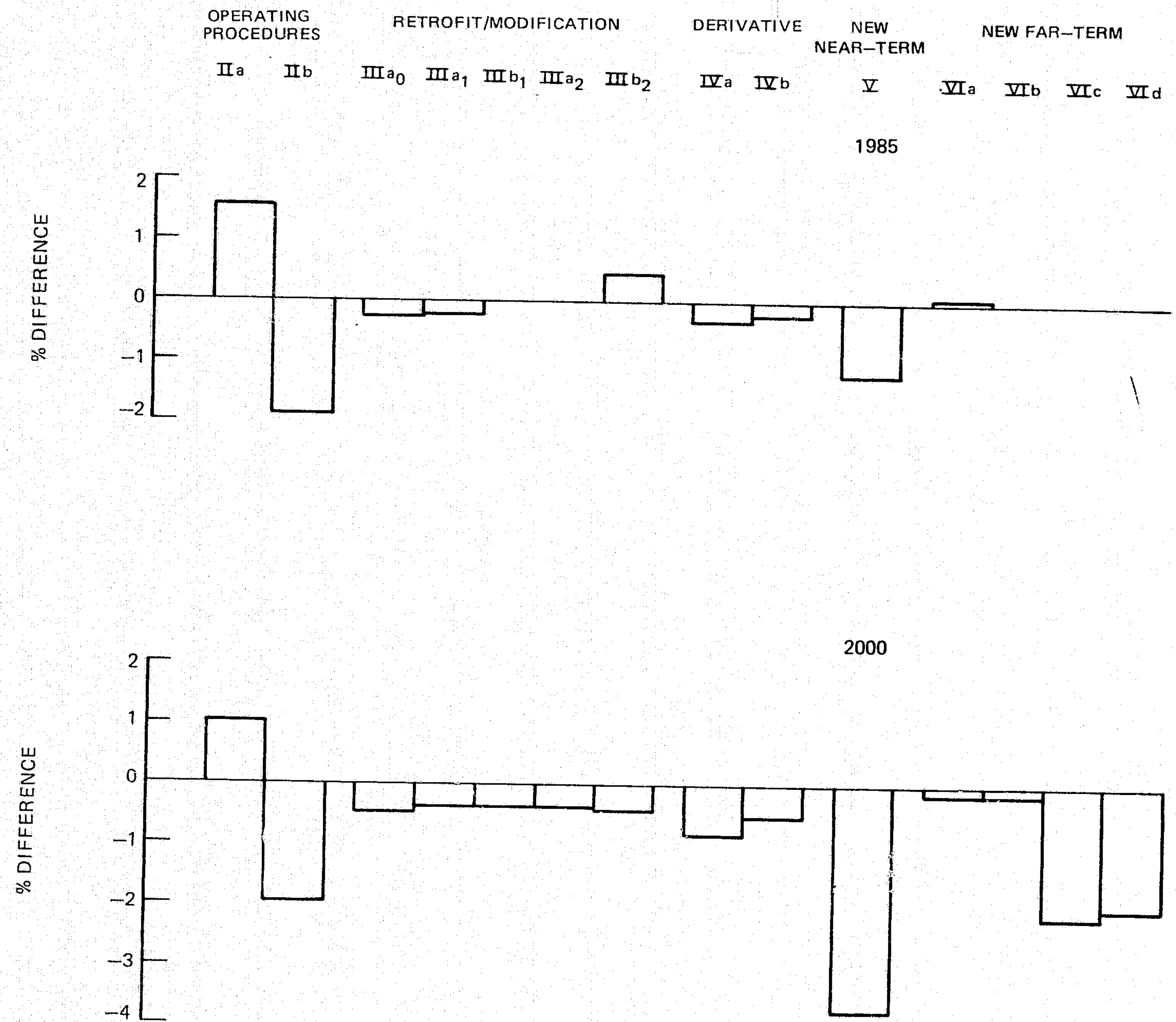

FIG. 34

The noise impacts on airports, as summarized in Fig. 30, clearly favor the derivative and new-aircraft options because the new aircraft are considerably quieter than baseline in-production models. The new near-term aircraft case, Option V, gives the most favorable results in both years, although it is closely followed by Options VIc and VId in the long term, and Option IVa is also good. Noise exposure is an impact for which the retrofit/mod options do not look attractive because they retain large numbers of older, noisier aircraft.

Government Impacts

Three parameters -- annual fuel usage, annual emissions, and cumulative R&D spending -- were selected as representative of government-related impacts. Although Fig. 31 shows that all options result in fuel savings relative to the baseline, it is clear that the derivative and new-aircraft options offer the greatest reductions in the long term, whereas short-term impacts are smaller and fairly equal over most of the options. The picture with regard to emissions is quite different, however. Results in Fig. 32 show that only the derivative and new-aircraft options yield appreciable emissions advantages. The retrofit/mod options are again seen to be unfavorable, as with noise, because older aircraft are retained longer. Fig. 32 shows that an important side benefit of the new-aircraft technology options is the large reduction in emissions they produce. It should also be noted that these results are relative to the baseline case, in which steady reductions in emissions occur as wide-body airplanes are assigned to replace retiring older models.

As shown in Fig. 33, the options dependent on advanced technology require large R&D investments by government, whereas the operational procedures with present ATC, retrofit/mod, and derivative options require no outlay of funds over the baseline. Option V appears quite attractive because only a minimal R&D investment is required to implement a present-technology, fuel-conserving aircraft design.

Air Traveler Impacts

Impacts on air travelers are described by fare differences compared with the baseline case, as shown in Fig. 34. Since passenger demand is inversely related to fare, the results in Fig. 34 are qualitatively opposite to those in Fig. 23. The options which show up well in the short term are Option IIb and Option V, while Option IIa is poor. In the long term, Option V is still superior, but two advanced-technology options (VIc and VId) are also favorable to air travelers. Although the percentage differences relative to the baseline are generally small for both forecast years, it appears that air travelers benefit most from improve- in ATC and aircraft technology. The retrofit/mod and derivative options produce small impacts.

BENEFIT/COST ANALYSIS

Introduction

All of the preceding discussion of results has emphasized the fuel-saving aspects of the alternative options investigated. The stimulation of demand, where it occurs due to improved quality of service, was shown to limit the absolute fuel saving despite improvements in fuel efficiency which is, in itself, a benefit/cost ratio (pass.-mi/gal fuel). However, the fuel savings shown were achieved along with other effects (variations in user cost and time, and in noise and emissions) and with, usually, a Government spending cost for the R&D required to accomplish the fuel saving.

Since many of these costs can be significant, and since they vary from option to option, a meaningful comparison of alternative options should account for the costs measured as well as the fuel saving achieved.

The UTRC Benefit/Cost Methodology is used to combine the various benefits and costs of a particular option into a single overall rating without resorting to artificial equivalences (to relate such diverse quantities as noise, emissions, Government spending, etc.) in order to evaluate their relative effects. This process involves the calculation of dimensionless, normalized, benefit/cost ratios, which are then combined into a benefit/cost rating using appropriate weighting factors for each cost element. The weighting factors can be derived in a pseudo-analytical fashion, as described in Ref. 14, or can be developed from an opinion survey as to the relative importance of each cost (as described in Ref. 19). The Benefit/Cost Methodology is fully described in Refs. 14 and 19; a brief description of its application in this study is given below.

The first step in calculating the benefit/cost rating is to normalize the defined benefits and costs of each option by the corresponding baseline values; thus,

$$b_i = B_i/B_o \text{ and } c_{ij} = C_{ij}/C_{oj} ,$$

where B_i and C_{ij} represent a single benefit and the j^{th} cost associated with option i, B_o and C_{oj} the corresponding baseline values, and b_i and c_{ij} the normalized values for option i. Fractional benefit/cost ratios, representing the amount of benefit provided per unit cost relative to the baseline, are calculated from

$$f_{ij} = b_i/c_{ij} \ .$$

A value of f_{ij} greater than 1.0 indicates that option i is superior to the baseline with respect to cost j (i.e., it provides more benefit per unit cost); a value less than 1.0 indicates the baseline is better. The benefit/cost ratios are combined into a benefit/cost rating using weighting factors ω_j for each cost:

$$R_i = \left[\prod_j f_{ij}^{\ \omega_j} \right]^{\frac{1}{\sum_j \omega_j}}$$

Again, a rating greater than 1.0 indicates superiority relative to the baseline.

Development of Benefits, Costs, and Weighting Factors

For the RECAT study, one benefit (enplaned passenger-miles) and six costs have been utilized in the analysis. The benefit value is taken directly from the simulation results; calculation procedures for the six costs for the 600 city-pair network are described below.

User cost and user time: These costs were calculated for origin-destination air travelers using all of the cost and time elements of disutility. These include both direct expenditures (fare and block time) as well as indirect cost and time, such as access, schedule inconvenience, destination transportation, etc. Since the 600 city-pair air network transports connecting passengers from other city-pairs, the total user cost and time were found by expanding the O-D values by the ratio of enplaned passenger-miles to O-D passenger miles.

Fuel: Fuel consumed, a direct output of the simulation program, was calculated by applying the fuel-vs-distance characteristics of each aircraft to the frequencies determined for each city-pair.

Government R&D spending: This cost was calculated by determining the year-to-year R&D program costs required to support each option and converting them to a total present value. The costs of separate R&D programs were estimated for options IIb (advanced air traffic control); IV (derivatives); V

(new near-term aircraft); VIa and VIb (new far-term turboprops); VIc (new far-term turbofans); and VId (new far-term turboprops and turbofans). The estimated annual spending for these programs, beyond the baseline R&D program, is presented in Table XXI. In addition, an R&D program of $124 million (1973$) annually has been estimated as necessary to support the baseline scenario. This figure is the average annual NASA spending for programs related to commercial air transportation for FY73-FY75. The spending programs were converted to cumulative present values using an 8 percent discount rate. This is done by weighting each year's spending by an appropriate factor; the result is the amount of money which must be set aside at the beginning of the period (1973) to fund the total program, assuming 8 percent annual interest. The cumulative present values for various periods for each program are presented in Table XXII. These amounts include both baseline spending and the additional expenditures shown in Table XXI. The Government R&D cost applicable to a particular option for a particular year is the cumulative present value for the period ending with that year taken from Table XXII.

Noise: The noise characteristics of each aircraft type actually used in the various options are presented in Table XXIII. Using these data, the air system noise was estimated relative to 1973 for a fictitious average airport having 260 takeoffs and 260 landings per day in 1973. This airport, defined to be typical of the air transportation network, is similar to the "23-Airport Average" of Ref. 15. The areas within the 15, 20, 30 and 40 NEF noise contours were estimated (assuming 15 percent of the flights are night-time operations). Next, the number of people highly annoyed by airplane noise was calculated by the method of Ref. 14 assuming an average population density over the noise-impacted area. This process was repeated for each forecast year and option using the mix of airplane types and the operational frequencies appropriate to each case. The assumption was also made that the population within the 15-NEF noise contour would increase at the same rate as the total projected population growth (1 percent per year) for the 247 SMSA's in the study.

Emissions: Airplane emissions were estimated based on the EPA landing and take-off cycle for each airplane type. The EPA cycle measures the pollutants produced during operations, including: 26 minutes at idle power setting, 0.7 minutes at take-off power, 2.2 minutes at climb power, and 4.0 minutes at approach power setting. This cycle was used to estimate five classes of pollutants for each airplane: carbon monoxide (CO), unburned hydrocarbons (UHC), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), and particulate matter (PM). The SO_x estimate was based on an average sulfur content of aviation gas turbine fuel of 0.065 percent by weight as reported in Refs. 16 and 17. Since the classes of pollutants are not equally noxious, a combined emissions index

TABLE XXII

GOVERNMENT R&D PROGRAMS

Annual Spending Beyond Baseline (10^6 1973 $)

Year	Adv. ATC (IIb)	Derivatives (IV)	New Near-Term Aircraft (V)	New Far-Term Aircraft: Turboprops 1985 (VIa)	Turboprops 1990 (VIb)	Turbofans (VIc)	TP + TF (VId)
1976	0	1.5	4	7	7	7	9
1977	10	0	13	35	32	35	38
1978	20	0	0	65	49	60	66
1979	20	0	0	91	61	110	121
1980	20	0	0	102	61	101	121
1981	20	0	0	25	54	43	74
1982	10	0	0	0	36	19	46
1983	0	0	0	0	20	0	20
1984	0	0	0	0	5	0	5
1985-2000	0	0	0	0	0	0	0
TOTAL	100	1.5	17	325	325	375	500

TABLE XXIII

GOVERNMENT R&D COSTS

Total Cumulative Present Value (10^6 1973 \$, 8% Discount)

Period	Baseline (I,IIa,III)	Adv. ATC (IIb)	Derivatives (IV)	New Near-Term Aircraft (V)	New Far-Term Aircraft: Turboprops 1985 (VIa)	New Far-Term Aircraft: Turboprops 1990 (VIb)	New Far-Term Aircraft: Turbofans (VIc)	New Far-Term Aircraft: TP + TF (VId)
1973-1980	712.6	754.5	713.7	724.4	890.7	839.0	898.1	922.7
1973-1985	980.1	1036.6	981.2	991.9	1170.7	1160.7	1195.9	1259.0
1973-1990	1162.1	1218.6	1163.2	1173.9	1352.7	1342.7	1377.9	1441.0
1973-2000	1370.3	1426.8	1371.4	1382.1	1560.9	1550.9	1586.1	1649.2

TABLE XXIV

AIRCRAFT NOISE AND EMISSIONS CHARACTERISTICS

Type	Noise (EPNdB) Takeoff(1)	Noise (EPNdB) Landing(2)	Total Emissions (lb/EPA cycle)	Combined Emissions Index (lb/EPA cycle)	Combined Emissions Index (lb/EPA cycle/seat)
B-747	106.3	105.7	242	71	0.18
DC-10/L1011	99.3	105.2	182	53	0.19
DC-8/B-707	116.7(JT4)/112.8(JT3D)	107.1(JT4)/116.6(JT3D)	242	35	0.23
B-727-100/200	99.7	106.9	76	23	0.23/0.17
B-737-200	96.5	108.0	51	16	0.16
DC-9-10/30	96.5	108.0	51	16	0.23/0.17
Turboprop	—	—	13	4	0.09
DC-8ER/B-707ER	97.6 ←(JT8D-209)→	102.0	102	32	0.21
DC-9-30D1	96.5	108.0	51	16	0.14
DC-9-30D2	—	—	57	18	0.15
B-727-300	—	—	81	24	0.15
DC-10-10D	96.5	103.2	147	43	0.22
DC-10-40D	—	—	212	62	0.19
L-1011-Short	—	—	182	53	0.27
L-1011-Long	99.3	105.2	208	61	0.15
N80-200-I	95.6	102.3	102	29	0.15
N80-200-L	—	—	64	19	0.10
N80-400-L	105.5	104.9	182	53	0.13
N85-200	92.7	104.3	50	15	0.07
N85-350	—	—	80	24	0.07
N85-500	95.6	107.2	96	29	0.06
N85-200P	92.7	104.3	28	12	0.06

(1) 3.5 nmi from brake release
(2) 1.0 nmi from threshold

(CEI) was determined as set forth in Ref. 18:

$$CEI = PM + \frac{NO_x}{1.37} + \frac{SO_x}{3.82} + \frac{UHC}{51.5} + \frac{CO}{107}$$

This equation is based on an assumed index of physiological tolerances; i.e., the body is 1.37 times more tolerant of NO_x than of particulates, 3.82 times more tolerant of SO_x than of particulates, etc. Table XXIII summarizes the emissions per cycle and CEI per cycle for the airplane types defined in the study. Since airplane usage varies with each option and forecast year, the CEI values in Table XXIII for each airplane were multiplied by their respective yearly operations rates and summed over all airplanes to obtain the total pollutants.

The annual benefits and costs for each year and for each option are summarized in Tables XXIV-XXVII. As noted above, the noise impact was related to the 1973 value for a fictitious airport merely to avoid the necessity to expand noise-impacted population to the total system, a parameter which could be subject to misinterpretation, yet no more useful for the benefit/cost analysis.

The following weighting factors were used to combine the six individual benefit/cost ratios into a single benefit/cost rating. These weighting factors represent an average of calculated values and the results of a survey of UTRC and NASA staff members (Ref. 19).

User Cost	0.151
User Time	0.240
Fuel	0.243
Government R&D	0.093
Noise	0.128
Emissions	0.145

Benefit/Cost Results

The methodology described above was used to derive the benefit/cost ratings presented in Table XXVIII. The interpretation of these results can be assisted by references to the individual fractional benefit/cost ratios (f_{ij}) which are presented symbolically in Tables XXIX-XXXII. Taken in combination, these tables can be used to illustrate the strong and weak points of each option in each forecast year.

(Text continued on page 137)

TABLE XXV

1980 BENEFITS AND COSTS

	Option	Pass.-Miles (10^9)	User Cost (10^9\$)	User Time (10^6hrs)	Fuel (10^9 gals)	Gov't R&D (10^6\$)	Noise (rel. to '73)	Emissions (10^3 tons)
I	Baseline	168.8	8.09	470.2	6.656	712.6	0.882	36.3
Ia	60¢/gal Fuel	143.4	7.57	403.2	5.587		0.884	30.5
Ib	Fuel Allocation: 70% Load Factor	164.9	7.88	468.5	5.315		0.723	30.6
IIa	Operating Procedures: Present ATC	159.3	7.84	451.2	6.187		0.863	34.3
$IIIa_0$	Retro/Mod: In-Prod. Only	170.0	8.11	473.5	6.356		0.885	36.6
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	170.9	8.13	476.1	6.436		0.941	37.1
$IIIb_1$	Retro/Mod: Aero + Eng. Proj. Ret.	168.9	8.09	470.4	6.329		0.875	36.5
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	170.0	8.12	473.7	6.701		1.076	38.3
$IIIb_2$	Retro/Mod: Aero + Eng. Del. Ret.	165.5	8.03	460.5	6.403		0.901	36.9

TABLE XXVI

1985 BENEFITS AND COSTS

	Option	Pass.-Miles (10^9)	User Cost $(10^9\$)$	User Time $(10^6$ hrs)	Fuel $(10^9$gals)	Gov't R&D $(10^6\$)$	Noise (rel. to 73)	Emissions $(10^3$ tons)
I	Baseline	224.1	10.62	626.5	8.440	980.1	0.958	46.7
Ia	60¢/gal Fuel	191.2	10.01	539.0	7.117		0.877	39.6
Ib	Fuel Allocation: 70% Load Factor	216.0	10.22	622.7	6.404		0.603	39.7
IIa	Operating Procedures: Present ATC	214.3	10.35	608.9	7.871		0.936	44.6
IIb	Operating Procedures: Advanced ATC	235.2	10.91	656.8	8.428	1036.6	0.951	49.7
$IIIa_0$	Retro/Mod: In-Prod. Only	225.3	10.63	629.9	7.987	980.1	0.958	47.1
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	225.1	10.64	629.1	8.078		0.990	47.5
$IIIb_1$	Retro/Mod: Aero + Eng., Proj. Ret.	224.3	10.62	626.9	8.060		0.980	47.3
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	224.6	10.64	627.5	8.176		1.027	48.0
$IIIb_2$	Retro/Mod: Aero + Eng., Del. Ret.	222.2	10.59	621.1	8.100		0.978	47.5
IVa	Derivatives:	225.3	10.62	631.0	7.961	981.2	0.895	45.0
IVb	Derivatives: No L-1011-Long	223.0	10.59	623.5	8.299	981.2	0.915	46.3
V	New Near-Term Turbofans	228.8	10.66	643.3	8.031	991.9	0.863	44.6
VIa	New Far-Term T'Props: 1985 avail.	223.4	10.60	625.1	8.165	1170.7	0.918	44.2

TABLE XXVII

1990 BENEFITS AND COSTS

	Option	Pass.-Miles (10^9)	User Cost (10^9\$)	User Time (10^6 hrs)	Fuel (10^9 gals)	Gov't R&D (10^6\$)	Noise (rel. to 73)	Emissions (10^3 tons)
I	Baseline	280.5	13.40	789.8	10.536	1162.1	1.059	59.1
Ia	60¢/gal Fuel	240.8	12.73	681.5	8.982		0.997	50.6
Ib	Fuel Allocation: 70% Load Factor	270.5	12.89	791.2	7.791		0.526	50.0
IIa	Operating Procedures: Present ATC	270.1	13.13	772.6	9.867		1.046	57.0
IIb	Operating Procedures: Advanced ATC	294.7	13.78	828.5	10.500	1218.6	1.061	62.7
$IIIa_0$	Retro/Mod: In-Prod. Only	282.4	13.43	795.1	9.944	1162.1	1.068	59.6
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	281.5	13.42	793.2	9.838		1.050	59.7
$IIIb_1$	Retro/Mod: Aero + Eng., Proj. Ret.	281.4	13.41	792.5	9.823		1.052	59.7
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	280.0	13.39	788.5	9.737		1.043	59.8
$IIIb_2$	Retro/Mod: Aero + Eng., Delayed Ret.	278.7	13.36	785.3	9.720		1.026	60.0
IVa	Derivatives:	283.7	13.45	800.9	9.494	1163.2	0.962	55.3
IVb	Derivatives: No L-1011-Long	279.2	13.40	786.2	10.256	1163.2	0.974	58.4
V	New Near-Term Turbofans	293.2	13.56	833.6	9.531	1173.9	0.873	53.7
VIa	New Far-Term T'Props: 1985 avail.	281.2	13.41	793.3	9.955	1352.7	0.973	52.7
VIb	New Far-Term T'Props: 1990 avail.	281.4	13.42	792.7	10.193	1342.7	1.020	54.7
VIc	New Far-Term T'Props:	285.2	13.49	806.6	9.649	1377.9	1.002	51.4
VId	New Far-Term T'Props & Fans	284.3	13.46	803.7	9.620	1441.0	1.006	51.5

TABLE XXVIII

2000 BENEFITS AND COSTS

	Option	Pass. Miles (10^9)	User Cost (10^9 \$)	User Time (10^6 hrs)	Fuel (10^9 gals)	Gov't R&D (10^6 \$)	Noise (rel to 73)	Emissions (10^3 tons)
I	Baseline	436.1	21.25	1246.0	16.400	1370.3	1.213	92.9
Ia	60¢/gal Fuel	379.2	21.45	1087.0	14.156		1.161	81.0
Ib	Fuel Allocation: 70% Load Factor	425.0	20.66	1253.3	12.516		0.562	78.8
IIa	Operating Procedures: Present ATC	423.9	20.92	1228.7	15.439		1.208	90.3
IIb	Operating Procedures: Advanced ATC	456.8	21.79	1300.9	16.376	1426.8	1.206	98.6
$IIIa_0$	Retro/Mod.: In-Prod. Only	439.1	21.28	1254.2	15.421	1370.3	1.210	93.6
$IIIa_1$	Retro/Mod.: Aero, Proj. Ret.	439.1	21.30	1253.8	15.337		1.207	93.8
$IIIb_1$	Retro/Mod.: Aero & Eng., Proj. Ret.	439.1	21.30	1253.8	15.319		1.210	93.8
$IIIa_2$	Retro/Mod.: Aero, Delayed Ret.	439.3	21.32	1254.1	15.252		1.203	93.9
$IIIb_2$	Retro/Mod.: Aero & Eng., Delayed Ret.	439.5	21.31	1256.1	15.200		1.181	94.0
IVa	Derivatives:	440.8	21.25	1264.6	13.751	1371.4	0.970	85.0
IVb	Derivatives: no L-1011-Long	432.3	21.22	1235.5	16.007	1371.4	1.032	92.7
V	New Near-Term Turbofans	461.7	21.47	1337.9	13.810	1382.1	0.868	79.7
VIa	New Far-Term T'Props: 1985 availability	436.3	21.23	1250.7	15.386	1560.9	1.008	81.6
VIb	New Far-Term T'Props: 1990 availability	436.4	21.25	1250.4	15.417	1550.9	1.024	81.5
VIc	New Far-Term Turbofans	448.0	21.26	1300.3	12.168	1586.1	0.903	58.7
VId	New Far-Term T'Props & T'Fans	447.1	21.25	1295.7	12.168	1649.2	0.935	59.0

TABLE XXIX

BENEFIT/COST RATINGS

	Option	1980	1985	1990	2000	Average 1973-2000
I	Baseline	1.000	1.000	1.000	1.000	1.000
Ia	60 ¢/gal Fuel	0.965	0.963	0.960	0.960	0.967
Ib	Fuel Allocation: 70% Load Factor	1.091	1.127	1.169	1.179	1.123
IIa	Operating Procedures: Present ATC	0.985	0.992	0.994	0.997	0.993
IIb	Operating Procedures: Advanced ATC	0.985	1.020	1.022	1.021	1.010
$IIIa_o$	Retro/Mod: In-Prod. Only	1.015	1.016	1.017	1.019	1.015
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	1.005	1.007	1.019	1.021	1.011
$IIIb_1$	Retro/Mod: Aero & Eng. Proj. Ret.	1.013	1.007	1.019	1.021	1.012
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	0.970	0.996	1.018	1.023	1.004
$IIIb_2$	Retro/Mod: Aero & Eng. Del. Ret.	0.990	0.999	1.017	1.026	1.008
IVa	Derivatives:	--	1.032	1.056	1.096	1.040
IVb	Derivatives: No L-1011-Long	--	1.008	1.015	1.020	1.009
V	New Near-Term Turbofans	--	1.046	1.096	1.155	1.064
VIa	New Far-Term T'Props: 1985 avail.	--	1.003	1.029	1.046	1.017
VIb	New Far-Term T'Props: 1990 avail.	--	--	1.013	1.045	1.012
VIc	New Far-Term Turbofans	--	--	1.045	1.197	1.051
VId	New Far-Term T'Props & T'Fans	--	--	1.038	1.185	1.047

TABLE XXX

1980 FRACTIONAL BENEFIT/COST RATIOS

	Option	User Cost (0.151)*	User Time (0.240)	Fuel (0.243)	Gov't R&D (0.093)	Noise (0.128)	Emissions (0.145)	Overall Rating
I	Baseline	0	0	0	0	0	0	0
Ia	60 ¢/gal Fuel	--	0	0	---	--	0	-
Ib	Fuel Allocation: 70% Load Factor	0	0	++++	-	+++	+++	++
IIa	Operating Procedures: Present ATC	-	0	0	--	-	0	0
$IIIa_0$	Retro/Mod: In-Prod. Only	0	0	++	0	0	0	0
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	0	0	+	0	--	0	0
$IIIb_1$	Retro/Mod: Aero & Eng., Proj. Ret.	0	0	++	0	0	0	0
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	0	0	0	0	---	-	-
$IIIb_2$	Retro/Mod: Aero & Eng., Del. Ret.	0	0	0	0	-	-	0

* Weighting Factor

KEY: Benefit/Cost Ratios

0	0.98-1.02		
+	1.02-1.05	-	0.95-0.98
++	1.05-1.10	--	0.90-0.95
+++	1.10-1.20	---	0.80-0.90
++++	>1.20	----	<0.80

TABLE XXXI

1985 FRACTIONAL BENEFIT/COST RATIOS

	Option	User Cost (0.151)*	User Time (0.240)	Fuel (0.243)	Gov't R&D (0.093)	Noise (0.128)	Emissions (0.145)	Overall Rating
I	Baseline	0	0	0	0	0	0	0
Ia	60¢/gal Fuel	--	0	0	---	--	0	-
Ib	Fuel Allocation: 70% Load Factor	0	-	++++	-	++++	+++	+++
IIa	Operating Procedures: Present ATC	0	0	+	-	-	0	0
IIb	Operating Proecdures: Advanced ATC	+	0	++	0	++	0	+
$IIIa_0$	Retro/Mod: In-Prod. Only	0	0	++	0	0	0	0
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	0	0	+	0	-	0	0
$IIIb_1$	Retro/Mod: Aero & Eng., Proj. Ret.	0	0	+	0	-	0	0
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	0	0	+	0	--	-	0
$IIIb_2$	Retro/Mod: Aero & Eng., Del. Ret.	0	0	+	0	-	-	0
IVa	Derivatives:	0	0	++	0	++	+	+
IVb	Derivatives: (no L-1011-Long)	0	0	0	0	+	0	0
V	New Near-Term Turbofans	0	0	++	0	+++	++	+
VIa	New Far Term T'Props: 1985 avail.	0	0	+	---	+	++	0

* Weighting factor

Key: Benefit/Cost Ratios

0	0.98-1.02		
+	1.02-1.05	-	0.95-0.98
++	1.05-1.10	--	0.90-0.95
+++	1.10-1.20	---	0.80-0.90
++++	> 1.20	----	< 0.80

TABLE XXXII

1990 FRACTIONAL BENEFIT/COST RATIOS

	Option	User Cost	User Time	Fuel	Gov't R&D	Noise	Emissions	Overall Rating
		(0.151)*	(0.240)	(0.243)	(0.093)	(0.128)	(0.145)	
I	Baseline	0	0	0	0	0	0	0
Ia	60¢/gal Fuel	--	0	0	---	--	0	-
Ib	Fuel Allocation: 70% Load Factor	0	-	++++	-	++++	+++	+++
IIa	Operating Procedures: Present ATC	0	0	+	-	-	0	0
IIb	Operating Procedures: Advanced ATC	+	0	++	0	+	0	+
$IIIa_0$	Retro/Mod: In-Prod. Only	0	0	++	0	0	0	0
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	0	0	++	0	0	0	0
$IIIb_1$	Retro/Mod: Aero + Eng., Proj. Ret.	0	0	++	0	0	0	0
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	0	0	++	0	0	0	0
$IIIb_2$	Retro/Mod: Aero + Eng., Del. Ret.	0	0	++	0	+	-	0
IVa	Derivatives:	0	0	+++	0	+++	++	++
IVb	Derivatives: No L-1011-Long	0	0	+	0	++	0	0
V	New Near-Term Turbofans	+	0	+++	+	++++	+++	++
VIa	New Far-Term T'Props: 1985 avail.	0	0	++	---	++	+++	+
VIb	New Far-Term T'Props: 1990 avail.	0	0	+	---	+	++	0
VIc	New Far-Term Turbofans	0	0	+++	---	++	+++	+
VId	New Far-Term T'Props + T'Fans	0	0	+++	---	++	+++	+

*Weighting factor

Key: Benefit/Cost Ratios

0	0.98-1.02		
+	1.02-1.05	-	0.95-0.98
++	1.05-1.10	--	0.90-0.95
+++	1.10-1.20	---	0.80-0.90
++++	> 1.20	----	< 0.80

TABLE XXXIII

2000 FRACTIONAL BENEFIT/COST RATIOS

	Option	User Cost (0.151)*	User Time (0.240)	Fuel (0.243)	Gov't R&D (0.093)	Noise (0.128)	Emissions (0.145)	Overall Rating
I	Baseline	0	0	0	0	0	0	0
Ia	60¢/gal Fuel	--	0	0	---	--	0	-
Ib	Fuel Allocation: 70% Load Factor	0	-	++++	-	++++	+++	+++
IIa	Operating Procedures: Present ATC	0	0	+	-	-	0	0
IIb	Operating Procedures: Advanced ATC	+	0	+	0	++	0	+
$IIIa_0$	Retro/Mod: In-Prod. Only	0	0	++	0	0	0	0
$IIIa_1$	Retro/Mod: Aero, Proj. Ret.	0	0	++	0	0	0	+
$IIIb_1$	Retro/Mod: Aero + Eng., Proj. Ret.	0	0	++	0	0	0	+
$IIIa_2$	Retro/Mod: Aero, Delayed Ret.	0	0	++	0	0	0	+
$IIIb_2$	Retro/Mod: Aero + Eng., Del. Ret.	0	0	++	0	+	0	+
IVa	Derivatives:	0	0	++++	0	++++	+++	++
IVb	Derivatives: No L-1011-Long	0	0	0	0	+++	0	+
V	New Near-Term Turbofans	+	0	++++	+	++++	++++	+++
VIa	New Far-Term T'Props: 1985 avail.	0	0	++	---	++++	+++	+
VIb	New Far-Term T'Props: 1990 avail.	0	0	++	---	+++	+++	+
VIc	New Far-Term Turbofans	+	0	++++	---	++++	++++	+++
VId	New Far-Term T'Props + T'Fans	+	0	++++	---	++++	++++	+++

*Weighting factor

Key: Benefit/Cost Ratios

0	0.98-1.02		
+	1.02-1.05	-	0.95-0.98
++	1.05-1.10	--	0.90-0.95
+++	1.10-1.20	---	0.80-0.90
++++	> 1.20	----	< 0.80

Effect of Fuel Allocation Measures

Referring to Table XXVIII, fuel allocation measures as applied to the baseline case (Ib) are seen to have the highest benefit/cost ratings of all options. These high ratings are directly related to higher load factors (70 percent rather than 58 percent). Tables XXIX to XXXII show that the fractional benefit/cost ratios which are most influential in these ratings are those with respect to noise because of heavy use of the relatively quiet B-747 and DC-10/L-1011 aircraft. Other ratios substantially greater than 1.0 are for fuel and emissions. Ratios less than 1.0 occur for user time (lower frequencies) and Government R&D (same cost as baseline, but lower benefit).

The 60¢/gal fuel cost scenario is consistently inferior to the baseline, with its major weak points being low benefit/cost ratios with respect to user cost, noise, and Government R&D. User cost increases because the higher fuel cost results in a fare increase. The fare increase depresses demand, thereby reducing the benefit, and as noted below, noise does not decrease correspondingly with the reduced demand.

Effect of Technological Fuel-Conserving Options

As shown in Table XXVIII, the operating procedures options (IIa and IIb) have benefit/cost ratings near 1.0, where improved procedures without benefit of advanced air traffic control (ATC) are less cost-beneficial than the baseline case ($R < 1.0$) despite a fuel saving; the provision of advanced ATC makes the option more beneficial than the baseline case ($R > 1.0$) despite the fact that very little fuel is saved because of increased demand. In addition to the increased demand, which helps all benefit/cost ratios (Tables XXX to XXXII), Option IIb is also favorable with respect to user cost, because of a fare reduction, and with respect to noise, since noise does not increase in proportion to demand*. The higher demand also manages to balance the R&D expenditure shown for the improved ATC in Table XXVII.

The retrofit/modification options (Options III) also have benefit/cost ratings near 1.0; as shown in Tables XXIX to XXXII, their only significant advantage, in benefit/cost terms, is due to the fuel savings achieved. In all other factors except noise, their benefit/cost ratios are either neutral or slightly negative; in terms of noise, these options which retain the older aircraft (a_1, a_2, b_1, b_2) show a distinct noise penalty in 1980 and 1985 (Tables XXIX and XXX).

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* With regard to noise, it appears that, for a given mix of airplanes, noise exposure does not vary appreciably with changes in demand. Therefore, in a case such as Option IIb, in which demand is higher than the baseline, the improved benefit is not balanced by a correspondingly higher noise exposure.

Among the technological options, the highest benefit/cost ratings (Table XXVIII) are associated with those options providing a replacement for the B-747 on short routes (i.e., IVa, V, VIc, and VId). As shown in Tables XXX to XXXII, all of these options offer substantial advantages (high benefit/cost ratios) in terms of fuel, noise, and emissions. The high Government spending incurred by the development of advanced technology, which shows up in adverse benefit/cost ratios for this cost item, is more than balanced by these favorable benefit/cost ratios. The turboprop-only options (VIa, and VIb) and the derivative option without the L-1011L (IVb) have lower ratings because of the limited impact achievable with new aircraft of 200-passenger, and smaller, sizes. The all-turbofan option (VIc) and the turbofan-plus-turboprop option (VId) are nearly identical in the overall ratings; the only significant difference being the higher combined R&D costs of the two development programs.

Summary of Benefit/Cost Results

In the near term (to 1985), significant gains can be achieved by the introduction of derivative aircraft (if the favorable characteristics of the L-1011L can be achieved), and further gains can be obtained by the introduction of new near-term turbofan aircraft.

In the far term, the development of new far-term aircraft, either turbofan-powered alone, or with both turbofan and turboprop powerplants, is decidedly cost beneficial, though through the year 2000 best results are achieved with only new near-term airplanes. In any case, the imposition of a fuel-allocation measure can enhance both fuel saving and benefit/cost rating, as evidenced by the gains due to this measure in the baseline case.

REGULATORY IMPLICATIONS

Introduction

The aviation industry is currently subject to a great deal of regulation, both economic and safety-related. Economic regulation by the Civil Aeronautics Board (CAB) embraces entry and exit, fares, industry structure and viability, and, less directly, many other aspects of the industry. At the present time there is extensive debate over the future of aviation regulation. The Administration favors significant deregulation, and the Congress is interested in some of the consumer benefits associated with such a change. The CAB itself has considered experimental deregulation and is pushing for procedural reform. Regulation is pervasive in its effects on the aviation system and must be taken into account in any attempt to project, or promote, system changes. In this section selected results having possible regulatory implications are summarized, and the regulatory impacts or changes are discussed with respect to these specific points.

RECAT Results with Possible Regulatory Implications

Frequency Restraints/Increased Load Factors

In a fuel allocation scenario, frequency reductions, or constraints on frequency growth, are essential. Even without fuel allocation, frequency growth limitations are required to avoid airside congestion. Carriers would be reluctant to do this voluntarily and might tend to reduce frequencies on noncompetitive or unprofitable routes rather than on competitive, high-frequency routes. As a result, maximum fuel efficiency with minimum adverse impacts would not be achieved. Thus, more government regulation of capacity might be required. The number of carriers in a given market, the types of airplanes they would be permitted to operate, etc., might be regulated, over and above present regulatory policy.

The operating cost economies brought about by very high load factors in a fuel allocation scenario would raise carrier profits. Lowering fares so that profits would be reduced to reasonable levels would stimulate demand, thereby increasing fuel use. To prevent this, the Government might tax this excess revenue, possibly using it to fund fuel-conserving technology developments or to subsidize the price of synthetic petroleum fuel.

Investments in New Aircraft

Fuel conservation in the near term can be effected by either retiring older-model turbojet- and turbofan-powered airplanes or by retrofitting them for improved fuel economy; aerodynamic modifications and reengining are the likely ways to reduce their fuel consumption. However, even after these changes, the older-model airplanes would still be less efficient than the new airplanes (current wide bodies) which would replace them, and retrofitting would delay replacement by from three to five years, possibly longer. Therefore, it appears that rapid retirement of older airplanes, particularly 4ENB models, would save fuel if the cost burden of replacement by new airplanes could be eased by Government policy, perhaps using tax credits, or by fostering sale of these airplanes to foreign carriers. Additional benefits would accrue in noise reduction and emissions if 4ENB aircraft are replaced in the U.S. fleet.

The impacts of fuel-conserving aircraft are more favorable to the public (through reduced noise and emissions) and to manufacturers (through sale of new, high-technology airplanes) than to airlines. However, these favorable impacts will not come about unless airlines are able and willing to purchase the new aircraft. Since the net present value of high-technology aircraft fleets is only slightly greater than fleets consisting of additional units of presently available aircraft, the problem is not one of influencing the choice of new purchases. Rather, what appears to be needed is a more attractive environment for carrier investment in new equipment, regardless of type.

Air Traffic Control

Improvements in air traffic control (ATC) would tend to reduce delays and thereby promote air transport system efficiency in terms of time as well as fuel. Although the costs of such improvements are not borne directly by the airlines (ticket taxes pay the bill via the Airport/Airways Trust Fund), implementation of ATC improvements may require that carriers refit their airplanes with special equipment to attain compatibility with the new ground-based ATC equipment (e.g., microwave ILS, vortex alleviation devices). If the cost of such equipment exceeds carrier expectations of potential savings, ATC improvements may not be effected, or may not achieve the maximum benefit.

Discussion of Regulatory Implications

Flight Frequency/Load Factors

The regulatory implications of conserving fuel by reducing or slowing the growth of flight frequency are extensive and complex, whatever means are used

to achieve the frequency change. Available means include the allocation of fuel, which directly forces each carrier to restrict operations, and the direct regulation of service frequency by the CAB. They also include less direct measures such as a change in the "Domestic Fare Investigation" standard load factor upon which fares are based (thus providing a strong economic incentive to the airlines), approval of voluntary interline agreements to reduce capacity, and expansion of charter-type operations.

Regulatory issues surrounding these approaches include:

1. Who shares in the resulting efficiency gains?

To the extent that it is the consumer who benefits through lower fares, the resulting increase in demand for air travel may reduce or negate system fuel savings. To the extent that it is the carrier who benefits, there are regulatory (and public policy) questions. The CAB is unlikely to freeze fares while increasing load factors and thus reducing costs. It would be possible, through direct regulation of frequency or manipulation of the CAB fare formulae, to share the benefit between consumers and carriers. It is also possible to create a tax which allows fares to remain near current levels but prevents the carriers from realizing unreasonable profits. This would of course require legislation and is not considered likely.

2. In what markets will the frequency reductions occur?

The danger is that direct allocation, with the airlines free to institute frequency cutbacks, will result in low-volume, low-profit service being cut rather than the highly competitive, high-volume markets. Such a result is probably unacceptable as a practical matter. The other approaches would, or could, be implemented so as to affect the high-volume markets. Capacity agreements, however, which have been permitted in the past to reduce frequencies, are currently looked on with disfavor by virtually all agencies of the federal government (including the Department of Justice, the Congress, and the CAB). Significant expansion of charter-type operations raises many questions and is unlikely unless it results in a sharp drop in travel cost (raising the demand-stimulation problem noted above). Direct regulation of frequency could clearly be tailored to achieve reductions (or control growth) in particular types of markets and in a way that either limits or permits demand increases. It does represent an additional form of regulation and thus goes somewhat against the grain of current thinking directed at less regulation.

3. What degree of load factor increase represents an unacceptable degradation in service?

The current load factor standards were not pulled out of thin air. Rather, they were the result of extensive deliberation and balancing of various economic, service, and social factors. Clearly there is a point at which high load factors imply service which is unacceptable in terms of ability to get a seat at a desirable time. This is of course more acute in low-volume markets but is of general concern. The standard is currently under review by the CAB.

New Aircraft Technology

The fuel-conservation options involving the adoption of new aircraft technology include aerodynamic improvements, engine refit, derivatives, and entirely new aircraft types. From the perspective of regulatory implications, each presents a similar problem, differing largely in degree. That problem is how to gain adoption of new technology in the absence of clear economic advantage to the airlines.

The problem is particularly difficult at a time when capital formation within the industry is of wide concern. Recent rates of return on investment for the trunk industry as a whole ranged from 1.4 percent to 7.8 percent (1970 - 1974), consistently below the rates identified by the CAB and most observers to be required to maintain a financially healthy industry. Individual lines, of course, have seen losses which have at times raised doubts about their ability to provide service.

In this setting, an approach involving mandatory adoption of new technology seems problematic. The precedent which exists in the area of noise-reducing technology is not encouraging in terms of the ease with which such adoption for fuel-conservation purposes might be mandated. Solutions involving mandatory adoption of new aircraft types seem unlikely.

Nonmandatory approaches would involve providing the airlines with the economic incentive to proceed with adoption of the new technology. This could be done by modifying current regulatory policy. An example is to favor, in route award decisions, air carriers which are adopting the desired equipment. There is currently little interest at the CAB in this type of modification of policy.

More direct incentives, such as tax incentives or direct subsidy, are possible, although either would require legislation. Informed observers

believe that subsidy of airlines from the Airport/Airway Trust Fund or general revenues, for the purpose of encouraging adoption of fuel-conserving aircraft technology, is an extremely remote one.

Advanced Air Traffic Control

The development and implementation of improved methods of Air Traffic Control (ATC) as a means to conserve fuel presents few problems in terms of regulatory implications. Historically, the federal government has directed and funded such activities primarily, but not solely, for safety-related reasons. Continuing improvement of the ATC technology is funded out of the Trust Fund supported by the ticket tax.

Demonstrable fuel savings resulting from new ATC technology, as estimated in Option IIb, may be a factor in the Congress' determination of appropriate funding levels for development and introduction of a next generation of ATC.

Requirements for on-board instrumentation for commercial aircraft to provide compatibility with new ground-based ATC does not present significant regulatory problems. Other precedents exist with many requirements for safety-related devices. Even though new systems may be in part intended to conserve fuel, the major justification for significant advances will be safety in an increasingly congested airspace.

Summary

The major regulatory implications of fuel-conservation measures boil down to three potential conflicts:

1. Fuel Conservation vs. Promotion of Air Travel

   Current law identifies as a goal of aviation policy the promotion of air travel. Any proposal to conserve fuel by means that involve the limiting of demand, or the failure to lower the cost of air travel if otherwise feasible, will be very difficult to implement. (The 55-mph speed limit is a rare instance of acceptance of a demand-dampening change in transportation policy. It is only partly analogous, however, since it involves safety as well as fuel conservation among its justifications.)

2. Fuel Conservation vs. Service

   To the extent that a conservation measure involves reduction in service it will face tough scrutiny in the CAB and the Congress.

Service to smaller communities is of particular importance, but even service reductions in high-volume markets will be difficult to achieve as they begin to affect the ability of the traveler to travel at about the time he or she chooses.

3. Fuel Conservation vs. Carrier Viability

Although of less regulatory importance than the two potential conflicts above, the current financial position of the carriers is of great concern. Conservation measures which significantly reduce carrier viability, such as uneconomic acceleration of new equipment adoption, will be difficult to implement.

In summary, the problems and potential conflicts between fuel conservation measures in aviation and other aspects of aviation policy are real. Successful achievement of conservation goals will require a coordinated consideration of regulatory and legislative implications.

CONCLUDING REMARKS

Although the major objective of this study has been to compare technological alternatives to achieving fuel conservation in the air transportation system, it has been shown that "actual" fuel usage is not the only consideration. If it were, then a solution which incurs enormous cost to the system, thereby raising operating costs and fares, thus reducing demand, would appear most attractive. Obviously, some balance must be struck between absolute fuel savings and maintenance of a viable air transportation system.

Comparative Measures

In this study, several devices have been used to express the relationship between fuel usage and system costs. Fuel efficiency, expressed in passenger-miles (or seat-miles) per gallon of fuel used, is a parameter which is appropriate to measure system performance as regards the way fuel is used. In effect, it modifies the parameter "actual fuel used" by introducing demand served as a consideration of equal importance. However, the drawback to fuel efficiency as a comparative measure is that it cannot be used to determine cumulative fuel used.

Another device which was employed in the presentation of results is "adjusted" fuel usage. With this parameter it becomes possible to compare options on the basis of cumulative fuel, and the problem of demand variations among options is eliminated by normalizing demand to the baseline value in each case. Thus, adjusted fuel used is a convenient measure of the "savings" in fuel relative to the baseline case.

Finally, the use of benefit/cost ratios has been utilized because it is a means of bringing additional considerations, such as noise, emissions, and government spending, into the comparisons. Fuel, user cost, and trip time enter, directly or indirectly, into the calculation of disutility which determines demand. Therefore, these parameters have an implicit effect on fuel used (actual or adjusted) and on fuel efficiency. However, noise, emissions, and government spending do not enter into the calculation of these other measures; they are considered only in the benefit/cost analytical process.

Summary of Results

In an attempt to summarize the totality of results for all options and to compare the fuel-conservation potential of each alternative, a set of summary

charts has been prepared in which the measures noted above have been employed. General results for cumulative demand, cumulative fuel saved, and average gain in fuel efficiency (defined as the ratio of cumulative demand to cumulative fuel used) are presented for the near term (1973-1985) in Fig. 35, and for the far term (1973-2000) in Fig. 36. These charts, which also give the benefit/cost ratings for each option, express the differences of each parameter relative to the baseline case, giving not only the absolute difference in the cumulative parameters (on the scale), but also the percentage differences (on each bar). An additional chart, Fig. 37, provides summaries of actual and adjusted cumulative fuel savings for selected options over various segments of the forecast period.

Considering first the near-term results in Fig. 35, note that, in terms of "goodness", all parameters have been selected to be better when they are positive and numerically high. In the case of benefit/cost ratings, numbers greater than 1.0 indicate an improvement relative to baseline values, whereas, in the other parameters presented, numbers greater than zero represent improvements. Also, results for the baseline sensitivity options are indicated by dashed lines to differentiate them from the technology-oriented results. Since fuel price and load factor variations may also be applied to any other option, these results are not meant to suggest alternatives to the technology options but additive effects which could be expected if these measures were adopted in combination with the other options. Therefore, their inclusion is primarily for reference rather than comparison.

The near-term results show that differences among the technology options are relatively small. Since derivative and new-aircraft fleets are rather small up to 1985, the beneficial effects of these advanced-technology options are not evident in Fig. 35. Respectable fuel savings are achieved by the operating procedures and retrofit/modification options, but the largest of these savings (IIa) is clearly due to depressed demand. This leaves only retrofit and modification as practical methods of conserving fuel in the near term. Of the five retrofit/mod options studied, the best are: $IIIa_0$, in which no retrofits to out-of-production aircraft are performed, and baseline retirement schedules are used; and $IIIb_1$, in which both aerodynamic and engine retrofits and modifications are performed with retirement schedules for out-of-production aircraft delayed only slightly (3-5 years) from the baseline.

Far-term results, as depicted in Fig. 36, are quite different from near-term results. Improvements occur in all cases, but the optimum derivative and new-aircraft options gain proportionally more than Options II and III. The end result is that the options tend to improve with advancing technology level, i.e., toward the right in the figure. As noted before, the retrofit/mod options merge to a common result in the long term, with cumulative fuel savings of about 5 percent and average fuel efficiency gains of about 6 percent.

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SUMMARY OF NEAR–TERM RESULTS; 1973–1985

RESULTS RELATIVE TO BASELINE

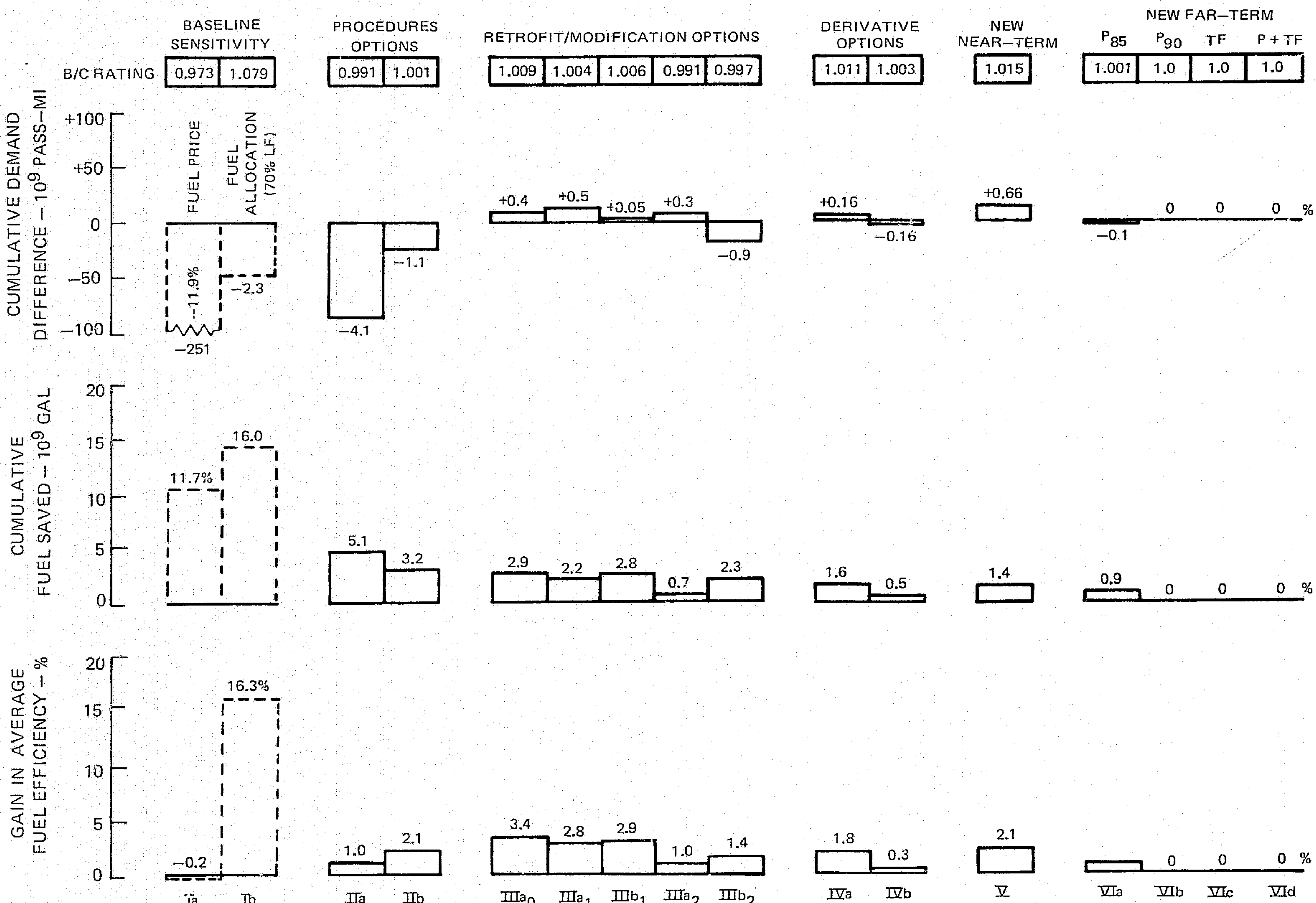

FIG. 3

147

76–03–71–10

SUMMARY OF FAR–TERM RESULTS; 1973–2000

ALL RESULTS RELATIVE TO BASELINE

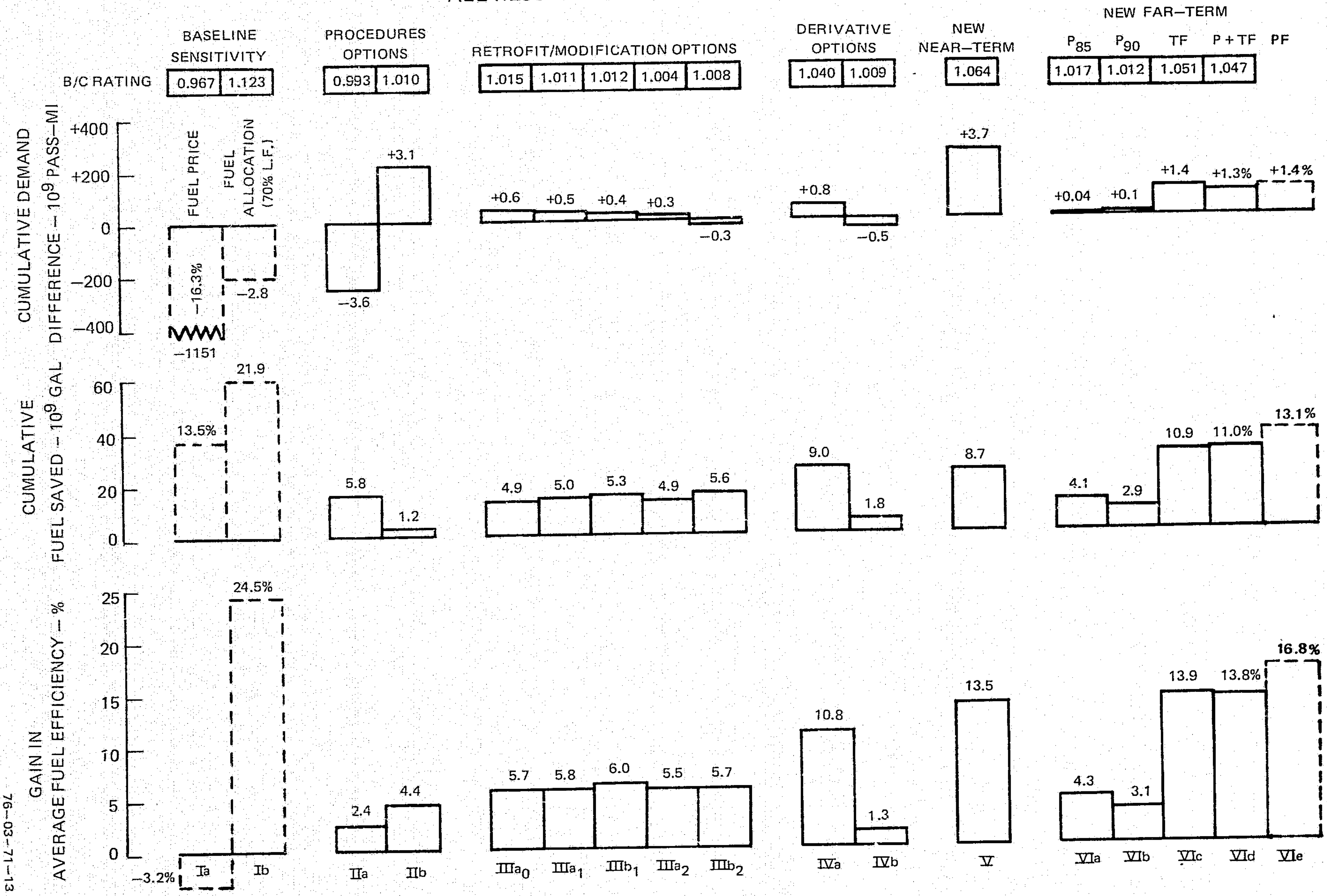

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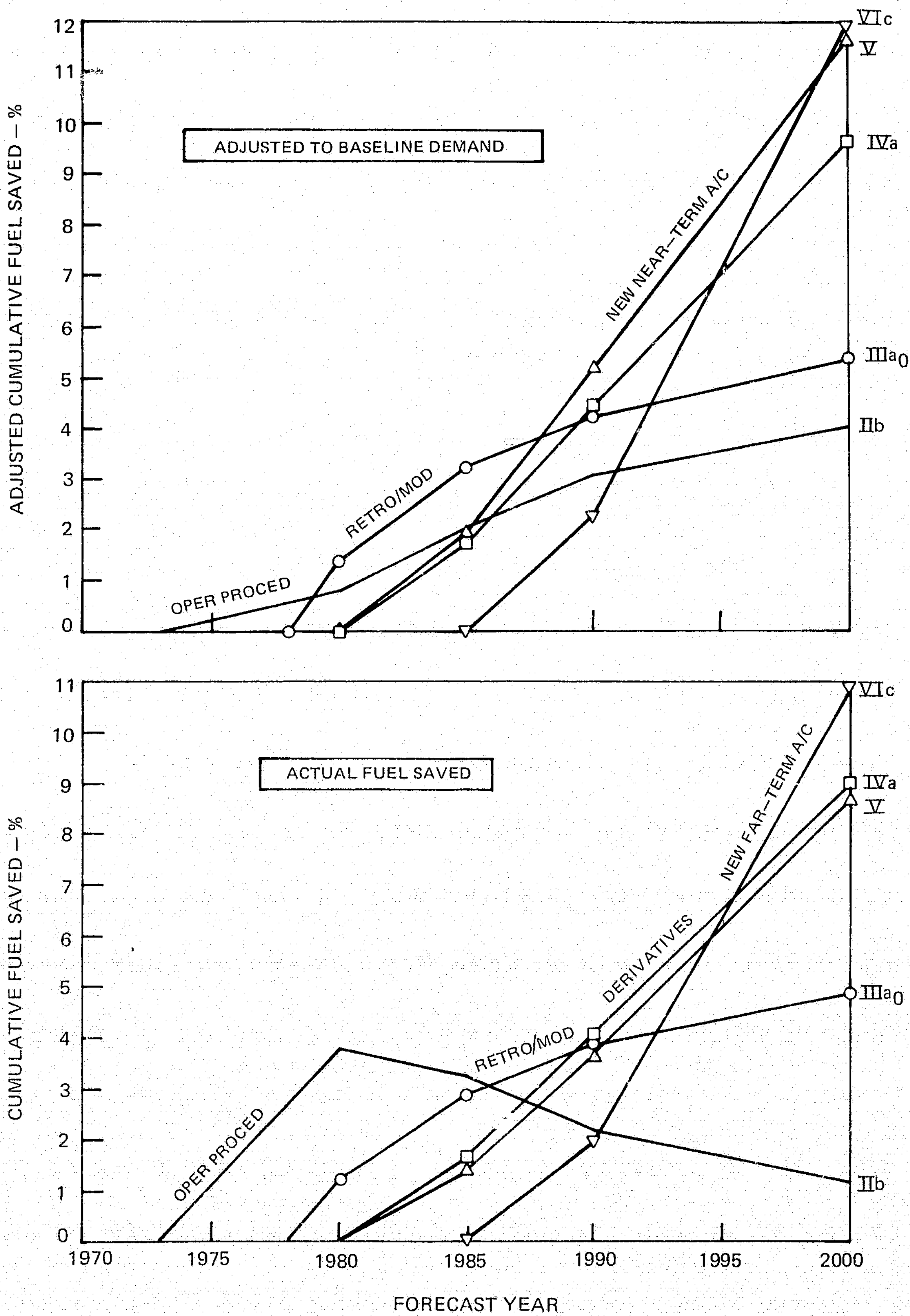
FIG. 36

CUMULATIVE FUEL SAVED THROUGH TECHNOLOGICAL OPTIONS



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However, the advanced-technology options achieve considerably more impressive long-term improvements over the baseline case. Particularly notable is Option V which combines the largest demand stimulation with a respectable cumulative saving in fuel and, in terms of average fuel efficiency, ranks with Options VIc and VId. The basic derivative option, IVa, also provides significant improvements over the baseline, and about double the retrofit/mod improvements.

As noted earlier (page 101), the computed results do not reveal the full potential of the propfan because a large propfan aircraft design was not made in the RECAT study. If it is assumed that a large propfan-powered airplane would have the same fuel efficiency advantage over a turbofan-powered airplane as it has in the 200-passenger size, and that the economic performance is about the same, then an all-propfan case can be estimated as shown in Case VIe of Fig. 36. These results, which are indicated by dashed lines to identify them as estimates, show that significant additional fuel savings may be achieved with propfans.

When consideration is taken of the benefit/cost ratings, the above discussion need not be qualified. In the near term, the ratings are all very close to 1.0, and those technology options which appear most attractive ($IIIa_0$ and $IIIb_1$) do not suffer from the additional considerations included in calculating the benefit/cost ratios. There are, however, some gains in relative ranking by Options IVa and V which place them in a slightly more favorable light. Considering its moderate fuel saving and superior benefit/cost rating, Option V may be a good near-term alternative from this broader perspective.

In the long term, the fuel saving advantages of the advanced technology options are further augmented by their high benefit/cost ratings. Furthermore, it appears that Option V achieves a slight edge because it has the highest benefit/cost rating (due to much lower Government spending relative to Option VI) and close to the highest fuel efficiency.

Thus, despite the many additional factors considered in the benefit/cost analysis, the implications are not significantly different than were found in the earlier comparison made primarily on the basis of fuel saved, thereby enhancing the confidence with which the study results can be regarded. This rapport is fortunate because it means that striving to save fuel is not inconsistent with efforts to improve the overall air transport system as measured by benefit/cost ratings.

Actual and Adjusted Fuel Savings

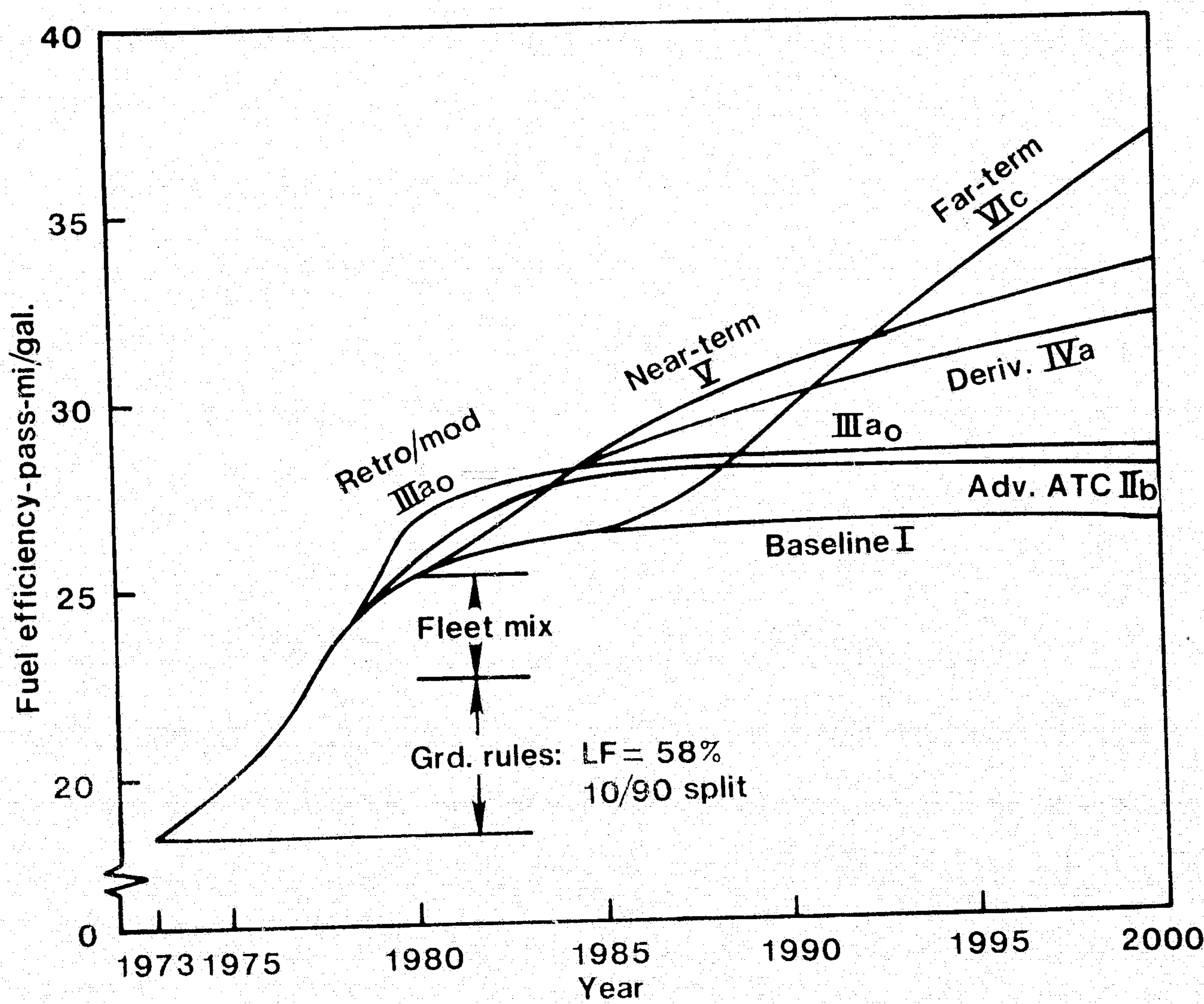
Some additional insights can be gained by comparing the options on the basis of actual and adjusted cumulative fuel savings continuously over the forecast period. This comparison is made in Fig. 37 for those technology options which achieved the best results in Figs. 35 and 36. The advantage of this presentation is that it makes possible a determination of the best option for any period out to the year 2000. Rankings in actual fuel saved in the previous two figures appear on the bottom half of Fig. 37 for 1985 and 2000. Also indicated are the numerical standings for all other years. Since the curves intersect in many places, it is apparent that these numerical rankings are strongly dependent on the period of years chosen.

Furthermore, it can be seen that the relative standings of the various options are not the same for adjusted savings as they are for actual savings. Since actual savings may be somewhat deceptive as an indication of fuel efficiency, the adjusted savings provide the better comparison. Based on this measure, three options (IIb, $IIIa_o$, and V) are the best alternatives for fuel conservation throughout the period. However, whereas IIb is the best choice up until 1979*, it is ultimately the worst choice (among the options depicted) by 2000. Similarly, Option V does not emerge as the best choice until 1988, and although Option $IIIa_o$ is dominant in the middle period, it is a poor long-term choice. Note that, at the very end of the forecast period, Option VIa becomes better than Option V by a small amount. However, due to the steep slope of the Option VIc curve, it would predominate in later years.

Further insight into the relative potential of alternative options can be gained by examination of the fuel efficiency trends presented in Fig. 38. These curves are not cumulative results, as in Fig. 37, nor are they gains over the baseline, as in Figs. 35 and 36; rather they are actual values of fleet fuel economy for each of the selected options in each of the forecast years connected by smooth curves to show the probable continuity. It is evident that a substantial gain is achieved, even in the baseline case, as brought about by both the ground rules of the study (load factor of 58 percent, 10/90 first class/coach split) as compared with historical (1973) practice, and the substitution and addition of the more-efficient wide-body aircraft into the fleet. The effects of those measures are felt strongly out to about 1980, but very little further gain is achieved in later years because of the limited opportunity to introduce a greater fraction of the newer aircraft, and because the wide bodies are used at increasingly shorter stages.

*For the period prior to 1980 Options IIa and IIb are the same.

FUEL EFFICIENCY TRENDS



Above the baseline are shown the additional gains in fuel economy achieved by the alternative options. Crossovers among the options are similar to those seen in Fig. 37 except that the effects of the more advanced options show up immediately upon introduction of the option rather than as effects accumulate, as in Fig. 37. Thus, crossovers occur earlier, an effect most noticeable in the case of the far-term aircraft option (VIc) which dominates beyond about 1992 rather than 1999, as in Fig. 37.

Although Fig. 37 is probably the single most descriptive exposition of the results which emerge from this study, it must be interpreted with care. Because the individual options defined for this study are very selective; i.e., each one specifies a particular fuel-conservation alternative, and combinations of options are not considered, not one of the individual options, including the baseline, can be thought of as a future scenario. Therefore, the interpretation of Fig. 37 must be that the savings indicated for any given option are probably the minimum that might be achieved. Additional savings can be achieved if certain options are combined, particularly if system improvements, such as Option IIb, are combined with aircraft technology improvements, such as Options IVa, V, and VI. On the other hand, some of the retrofit/mod options may not be very compatible with the advanced-technology options because retention of older-model aircraft may delay assignment of new designs, thereby reducing fuel savings.

To a first approximation, some of the options given in Fig. 37 are additive. For example, the combination of Option IIb with Option V would result in a cumulative adjusted fuel saving of about 15 percent in the year 2000, and the combination of Option IIb and VIc would save about 6 percent. Because of the problem noted above in connection with the incompatibility of retrofits and new-aircraft options, such combinations are not quite additive. For example, the combination of Option $IIIa_o$ with Option V results in a 14.2 percent saving in 2000 rather than 15.5 percent which would result from adding the two. Similarly, the combination of Option $IIIa_o$ and VIc results in 15.5 percent rather than 17 percent.

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APPENDIX A

TOTAL FUEL USAGE BY U.S. CERTIFICATED CARRIERS

Since the fuel use figures given in the main text refer specifically to the 600 city-pair system, it is of interest to consider the extrapolation of these data to the total domestic system. At the same time, the fuel used by U.S. carriers in cargo and international service can be added to the baseline domestic figures to obtain an estimate of total fuel usage by all U.S. certificated carriers.

The extrapolation of fuel from the 600 city-pair system to the domestic total is based on the 1973 enplaned passenger-mile and air system fuel efficiency data in Table VI. In any forecast year, total domestic fuel usage is determined by scaling the 600 city-pair fuel figure using the ratios of enplaned passenger-miles and fuel efficiency in the first two columns. If F_{Y600} is the 600 city-pair fuel in a forecast year, total domestic fuel in that year, F_{YTOT}, is:

$$F_{YTOT} = F_{Y600} \frac{126.5 \times 10^9}{107.5 \times 10^9} = 1.35\ F_{Y600}$$

This conversion reflects the fact that the fuel efficiency in the 600 city-pair system is higher than the system average because the average stage-length and average airplane capacity are higher. In effect, it indicates that almost 3/4 of the domestic fuel is burned on the 600 city-pair routes.

Cargo and International Fuel Use

Estimates were made of the fuel used by U.S. all-cargo and international carriers in the forecast years. The procedures used to make these estimates do not approach the level of detail included in the estimation of fuel used in domestic passenger operations. However, they account, in a relatively crude way, for fuel used in these operations and, when added to domestic consumption, provide a figure representative of total U.S. air carrier fuel usage. In the following paragraphs, the methods of forecasting cargo and international fuel consumptions are described, and the results are presented for the entire forecast period of study (1973--2000).

Projection of Fuel Used in All-Cargo Operations

Inasmuch as the study emphasizes the projections of passenger travel, it does not consider explicitly the energy requirements of freight transportation

except as an adjunct to passenger transportation through the use of belly cargo compartments in passenger aircraft. Belly cargo is, of course, not insignificant and, with the advent of wide-body aircraft, has often been blamed for the failure of the air cargo market to develop as rapidly as had been predicted. Nevertheless, a significant all-cargo market does exist and its fuel requirements should be projected along with those of passenger air transportation.

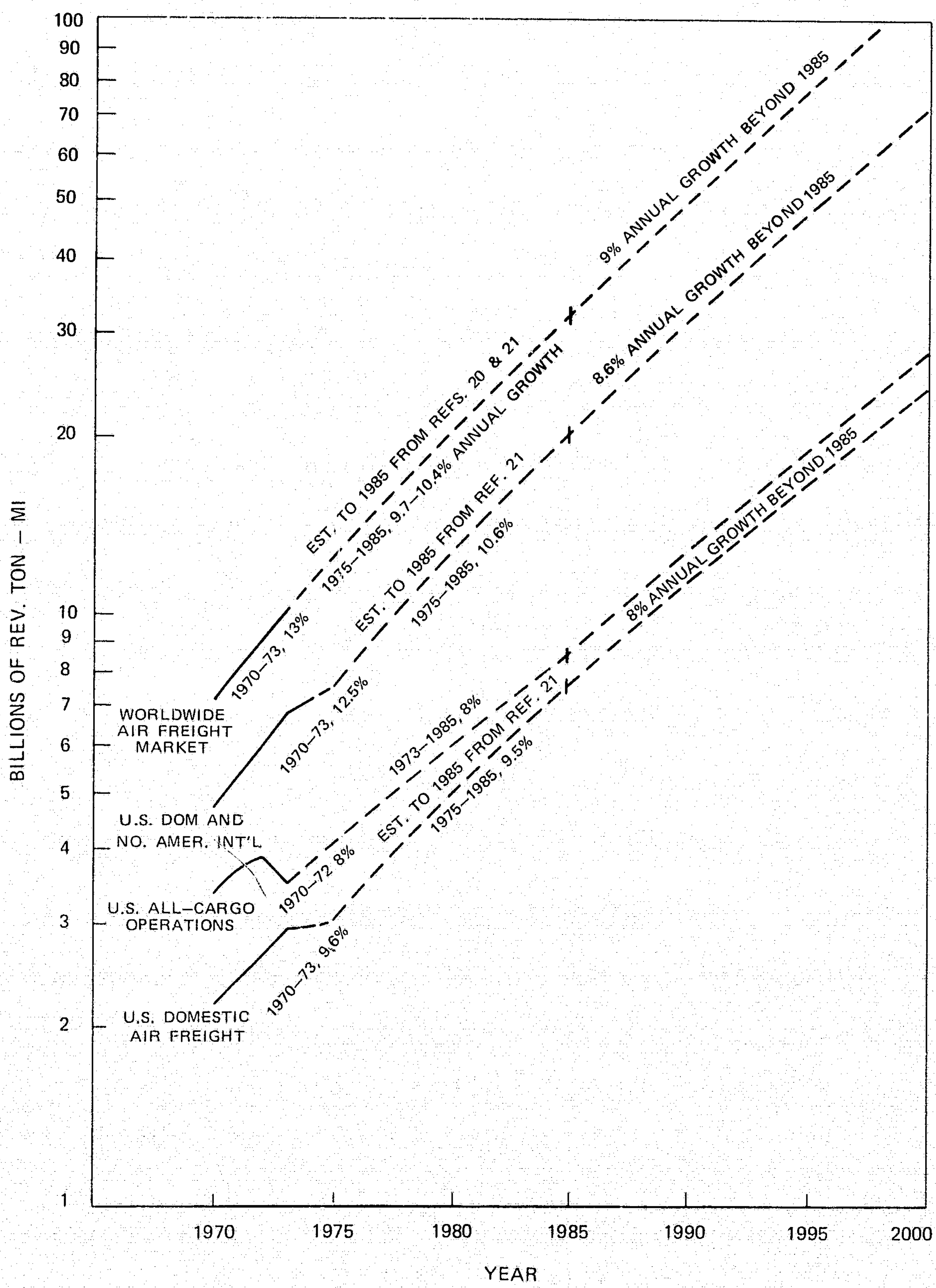
The worldwide freight market has been predicted (Refs. 20 and 21) to grow as shown in Fig. 1. Pertinent segments of this market (U.S. domestic and North American international) are also shown in Fig. 1 as projected in Ref. 21. In these references, the 1975-to-1985 worldwide growth is about 10 percent annually, where the U.S. domestic freight growth is 9.5 percent, and the combined U.S. domestic plus North American international growth prediction is about 10.6 percent annually. For the post-1985 period, average annual RTM growth rates of 9 percent worldwide and 8.6 percent for combined U.S. domestic plus North American international were assumed.

From CAB statistics (Ref. 22), all-cargo revenue ton-miles (RTM) were calculated for the years 1970 to 1973 and are also shown in Fig. 1. These values must be calculated by summing the operations of the different types of operators (trunks, all-cargo, etc.) and airplanes (4-turbofan regular body, etc.) because only scheduled values are given in a summarized statistics such as are presented in Ref. 23. It is seen that there was growth in all-cargo operations between 1970 and 1972 but a significant decrease between 1972 and 1973. While a two-year period is not statistically meaningful in establishing a trend, the 1970 to 1972 period showed an average annual growth of 8 percent. This is considerably lower than the total air freight growth in the various segments noted in this period, but a lesser all-cargo growth should be expected because of the introduction, in this period, of the wide-body passenger airplanes which offered large belly cargo capacity.

If one were to ratio the all-cargo operations growth in this period (8 percent) to the growth of total cargo operations (13 percent) and apply this ratio to the approximate 10 percent growth of the total market predicted for the 1975-to-1985 period, a resulting growth rate for all-cargo operations would be about 6 percent annually. However, with the introduction of wide-body all-cargo aircraft as is currently being done by Northwest Orient, Seaboard World, and Continental, it is expected that all-cargo operations will capture a larger share of the total cargo market, particularly as the growth of the passenger fleet capacity (and belly cargo) is expected to be lower (6 percent to 8 percent, Ref. 20) than freight. Accordingly, a projection of 8 percent annually has been assumed from the last data point (1973) available for all-cargo revenue ton-miles. As shown in Fig. 1, this results in a U. S. all-

FIG. 1

AIR FREIGHT PROJECTIONS



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freight market of about 8.8 billion RTM in 1985 and 28 billion RTM in the year 2000.

While the fuel used in all-cargo operations can be calculated for previous years using the CAB statistics (Ref. 22), it is not logical to merely apply a growth rate based on RTM to these values because the introduction and increasing use of the fuel-efficient wide-body aircraft will produce fuel savings which can be at least estimated. Accordingly, an attempt was made to project the RTMs expected for each aircraft type, and then apply a fuel intensity value to calculate the fuel used by each type, values which can then be summarized for an overall fuel projection of all-cargo operations.

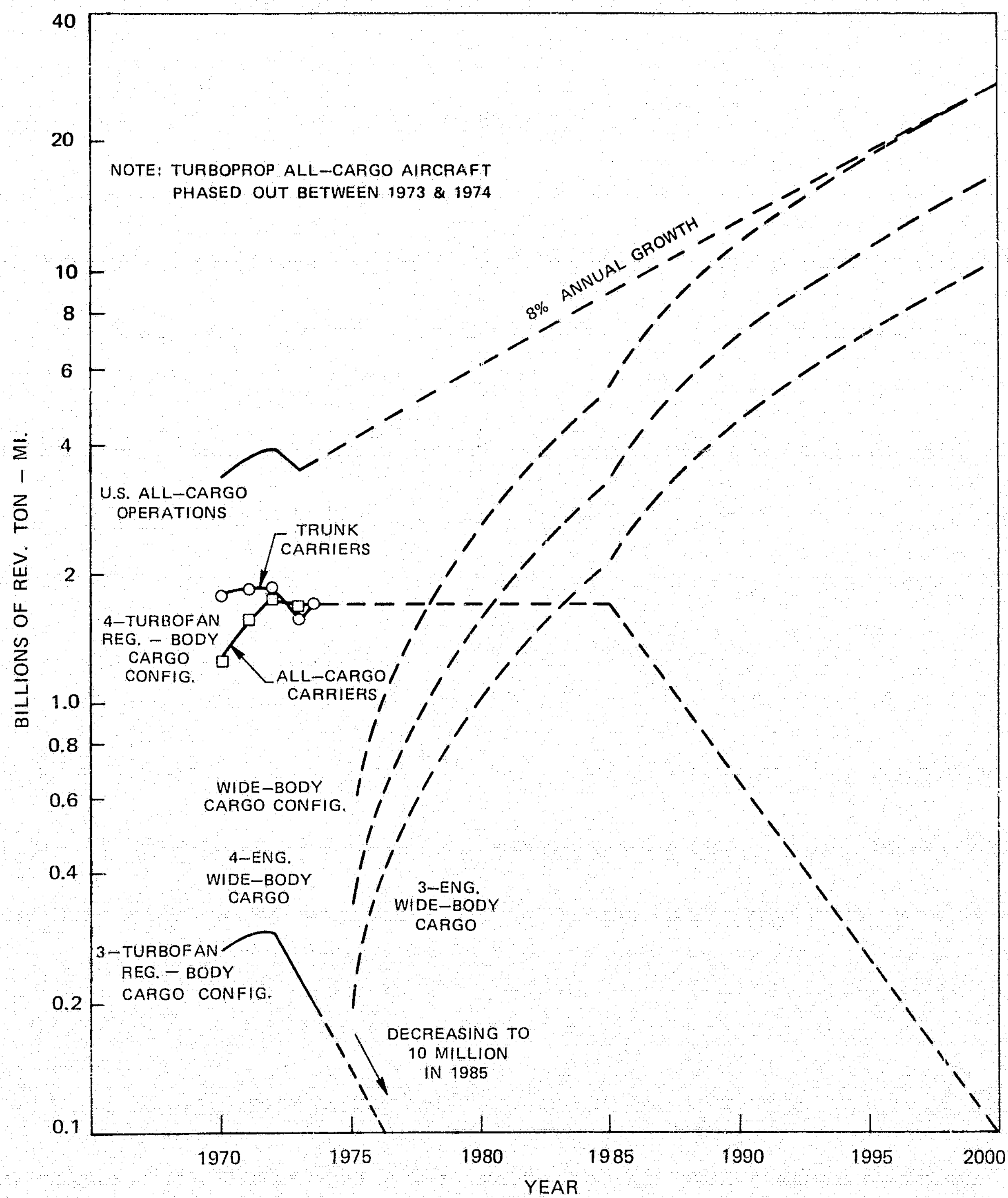
Based on CAB data (Ref. 22), the revenue ton-miles of the aircraft types in operation up to 1973 were calculated and are shown in Fig. 2*. Because four-engine regular-body cargo aircraft tend to be loaded more heavily by all-cargo carriers, and produce better fuel economy, these types were separated between trunk and all-cargo carriers. As shown in Fig. 2, the data do not lend themselves to establishing a clear trend. Therefore, it has been assumed that the RTM for these aircraft will reach a level of 1700 RTM/yr in 1975 and will remain at that level out to 1985, at which time they will begin a decline assumed to reach 100 million RTM in the year 2000. Beyond 1975, all-cargo growth is assumed to come in the form of the introduction of wide-body all-cargo aircraft. Based on the trend shown in Fig. 2, the use of 3-engine regular-body all-cargo aircraft appears headed downward and the trend has been simply extrapolated to 10 million RTM in 1985 and phased out after that.

Adding the trends for the regular-body cargo aircraft shown in Fig. 2 and subtracting from the projected RTM for all-cargo operations given in Fig. 1 leaves the RTM expected for wide-body cargo aircraft, as shown in Fig. 2. It is really too early to tell how this will be split between 4-engine (B-747) and 3-engine (DC-10) aircraft; orders currently on the books suggest about a 60/40 split in RTM. The precise split is not too important for the projection of all-cargo fuel use since both aircraft are quite fuel-efficient compared with conventional aircraft. Using the assumed split, the RTM trends are as shown in Fig. 2.

CAB data (Ref. 22) permit the calculation of fuel intensity (gal/RTM) of all-cargo aircraft for those types in operation in 1973. Since wide-body all-cargo aircraft were not in operation in that year, the fuel intensity of such

* Note that turboprop aircraft, though included in the historical calculations, are not shown in Fig. 2 because their productivity was less than 60 million RTM after 1970 and were phased out between 1973 and 1974.

U.S. ALL–CARGO PROJECTIONS



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aircraft must be estimated based on the fuel consumption and speed characteristics of wide-body passenger aircraft and known cargo capacity of wide-body all-cargo aircraft. These calculations are given in Table I, and summarized values of fuel intensity estimated for the present study are shown below:

Operator	Aircraft	Gal/RTM
Trunk	4TF, R-B	0.218
All-Cargo	4TF, R-B	0.163
-	3TF, R-B	0.280
-	4TF, W-B	0.102
-	3TF, W-B	0.160
-	4TP	0.255

Applying these fuel intensity values to the revenue ton-mile projections of Fig. 2, the estimate of fuel used, shown in Fig. 3, is obtained. It is seen that whereas the all-cargo RTM projection represents an 8 percent annual growth to 1985, the improved fuel efficiency of the wide-body aircraft now being introduced results in an overall fuel projection having only 5.8 percent annual growth to 1985. Projections beyond 1985, based on the extrapolated RTM data given in Fig. 2, give an average growth in fuel consumed of 6.7 percent/year.

Projections of Fuel Used by U.S. International Passenger Carriers

Fuel consumed by U.S. international passenger carriers was estimated by a method similar to that used for cargo. Projections were first made for the traffic volume in revenue passenger miles (RPM), fuel intensities were specified for each aircraft type appropriate to the forecast years, and fuel usage was projected as the product of these components.

Of the various projections of future RPM growth in the international passenger market, those presented in Refs. 20, 21, and 24 represent a spectrum of viewpoints, including manufacturer, operator, and independent forecasters. These forecasts range from optimistic to pessimistic, as shown in Table II. They are in agreement in only two respects, namely the marked decline in growth relative to historical data and the unequal growth by sectors.

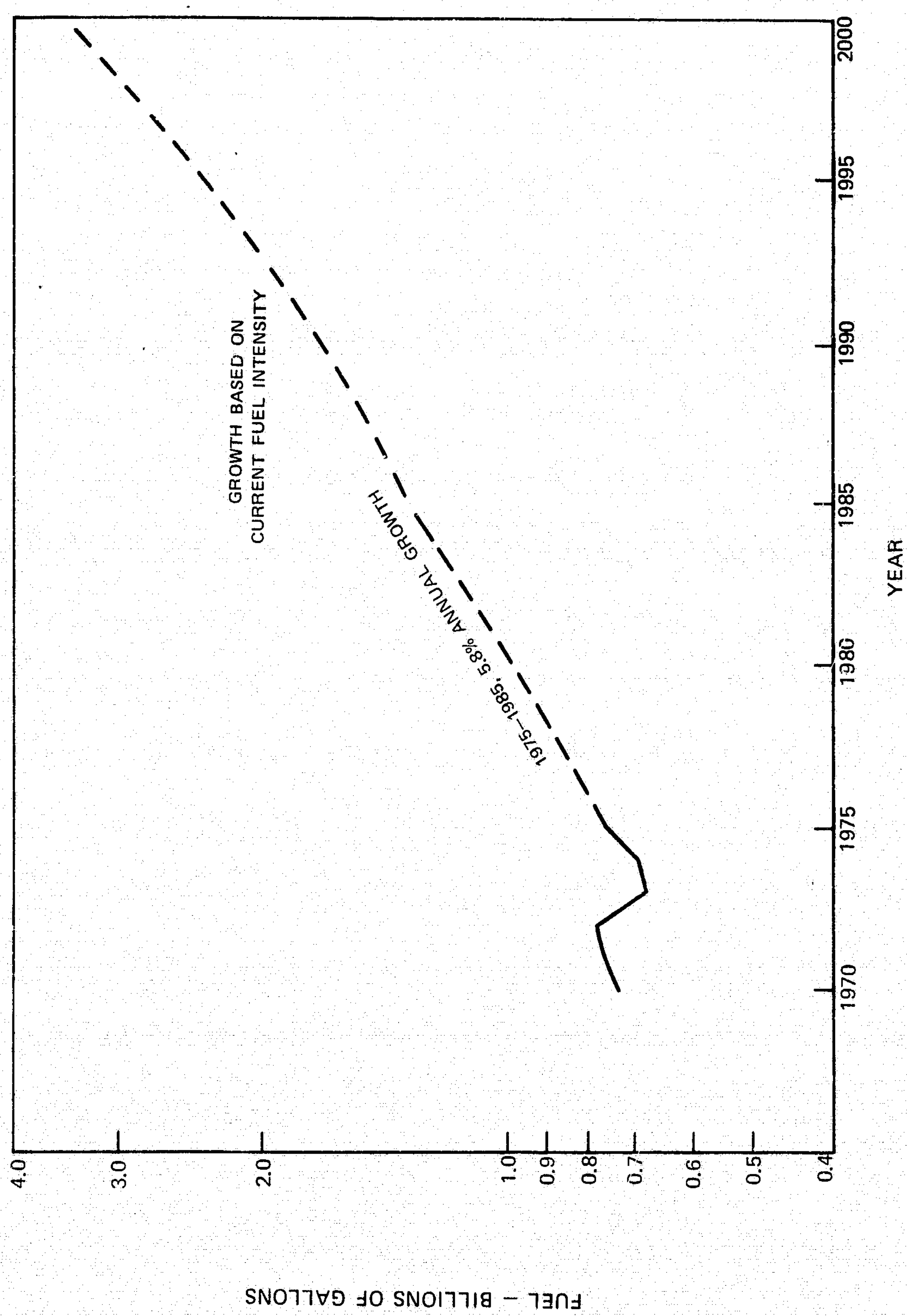
TABLE I

FUEL INTENSITY OF TRANSPORT AIRCRAFT
(1973 C.A.B. Data)

OPERATOR	OPERATION	A/C TYPE	REV. TONS	GAL/BL. HR	BL. SPEED	GAL/RPM
Trunk	Dom., Pass.	4TF, W-B	19.0	3388	456	0.39
Trunk	Int., Pass.	"	24.9	3598	470	0.307
Trunk	Dom., Pass	4TF, R-B	8.2	1765	412	0.52
Trunk	Int., Pass.	"	9.9	1866	447	0.422
Trunk	Dom., Pass.	3TF, W-B	12.6	2236	412	0.431
Trunk	Int., Pass.	"	15.5	2652	449	0.381
Trunk	Dom., Pass.	3TF, R-B	6.6	1313	357	0.557
Trunk	Int., Pass.	"	6.9	1503	386	0.564
Trunk	Dom., Cgo.	4TF, R-B	20.9	1860	420	0.212
Trunk	Int., Cgo.	"	19.1	1876	451	0.218
All-Cgo.	Dom., Cgo.	"	29.6	2041	416	0.166
All-Cgo.	Int., Cgo.	"	29.5	2166	452	0.162
Trunk	Dom., Cgo.	3TF, R-B	12.0	1377	410	0.280
All-Cgo.	- , Cgo.	4TF, W-B	~76.5*	~3600	~460	0.102
All-Cgo.	- , Cgo.	3TF, W-B	~37.5*	~2600	~430	0.160
-	- , Cgo.	4TP	8.7	675	273	0.255

* Cargo Load Factor estimated at 60% in years subsequent to 1974. Based on trend of system load factor for all-cargo operations starting at 51% in 1970 and reaching 59% in 1974.

FIG. 3



GROWTH IN FUEL CONSUMPTION
U.S. ALL–CARGO OPERATIONS

TABLE II

Summary of RPM Growth Rates

International Air Passenger Carriers
Ref. 20/Ref. 22/Ref. 24

RPM Growth Rates in Percent

Sector	← Historical →		← Projected →		
	1960-1970	1970-1974	1970-1975	1975-1980	1980-1985
Atlantic	16.5	2.9	4.5/-/-	6.9/-/6.4	5.4/-/-
Pacific	13.5	-0.6	12.7/-/-	14.0/-/8.1	11.0/-/-
Latin America	17.1	0	13.0/-/-	13.5/-/9.0	12.1/-/-
TOTAL	15.9	1.1	8.8/7.4/-	10.4/8.9/7.5	8.6/7.0/-

A summary of RPM projections adopted for this study is shown in Fig. 4. The growth rates by sector, which are noted in the inset, were adapted from the data in Table II. The contrast in future RPM growth relative to the 1958-1973 period is apparent.

Considering the base year for this study (1973) it is of interest to see how RPMs and fuel were distributed by aircraft category. Using Ref. 23 as the source of these data, Figs. 5 and 6 were prepared to show this breakdown. Note that four-engine wide-body aircraft generated the most RPMs of any aircraft type, but were second to four-engine regular-body aircraft in fuel usage. Of the remaining categories, turboprop and turbojet aircraft accounted for only minor shares of RPM and fuel, and both have declined further since 1973.

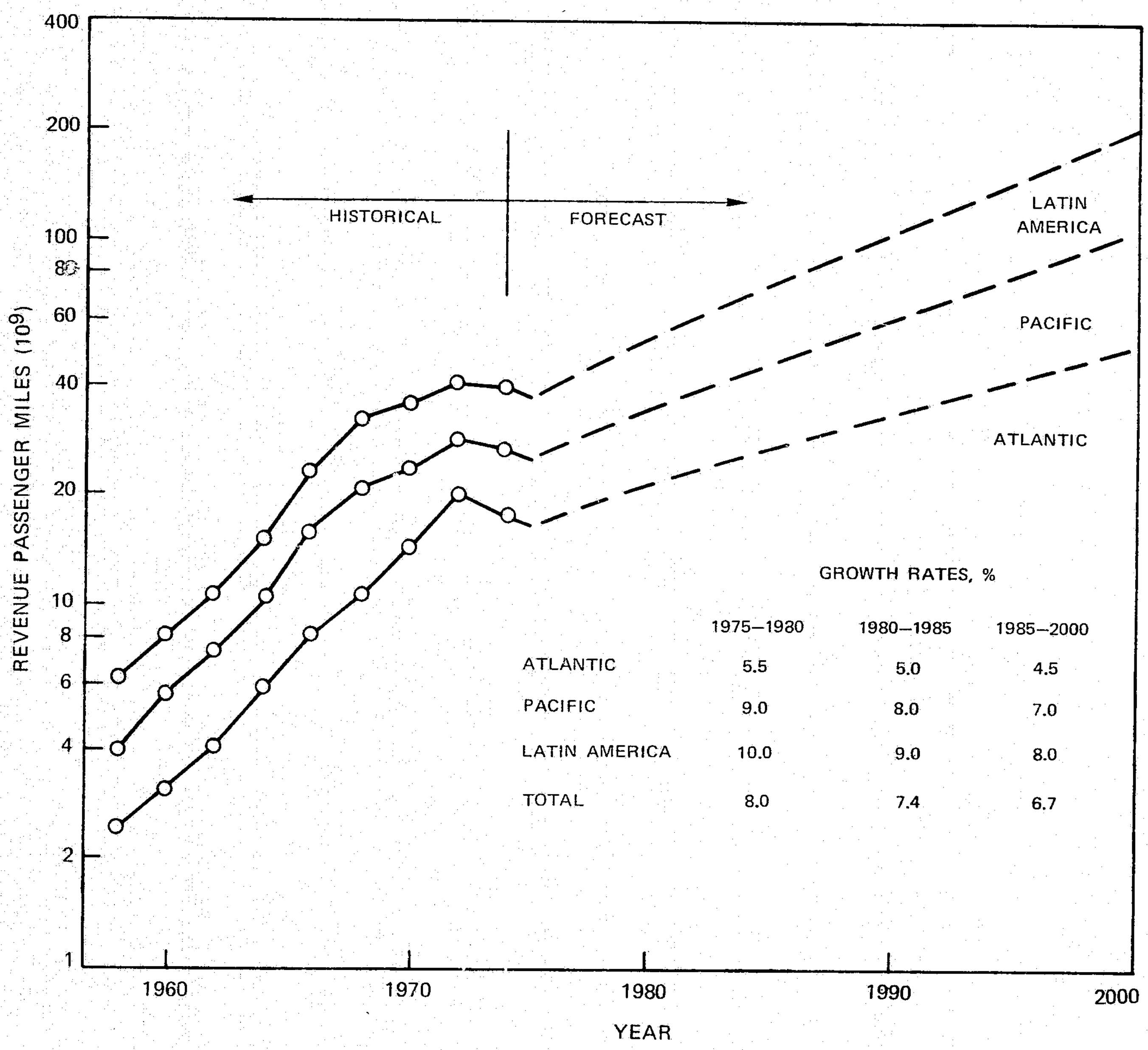
Three-engine wide-body aircraft had not made a significant impact in 1973, but their utilization on international routes can be expected to increase at the expense of three- and four-engine regular-body aircraft. Assuming that these latter aircraft types will be phased out by the late 1980s and early 1990s, wide-body aircraft will eventually dominate in all sectors. A summary of this assumed changeover is given in Table III in terms of both RPM and fuel consumed by sector and by aircraft type. The RPM data were taken from Fig. 4 and fuel intensities for each aircraft category were based on the following 1973 data from Ref. 23.

Aircraft Category	Average 1973 Fuel Intensity, Gal/RPM
Four-Engine Wide-Body Turbofan	0.04120
Four-Engine Regular-Body Turbofan	0.05262
Three-Engine Wide-Body Turbofan	0.04577
Three-Engine Regular-Body Turbofan	0.05891
Four-Engine Regular-Body Turbojet	0.06708
Four-Engine Regular-Body Turboprop	0.06270

As the more-fuel intensive aircraft are retired, overall fuel intensity of the international passenger aircraft fleet decreases with time, as shown at the bottom of Table III. Thus, the growth of fuel usage is less than RPM growth. The estimate of total fuel is illustrated in Fig. 7 by sector and by year throughout the forecast period.

PROJECTIONS OF INTERNATIONAL RPM GROWTH

U.S. INTERNATIONAL CARRIERS



GROWTH RATES, %

	1975–1980	1980–1985	1985–2000
ATLANTIC	5.5	5.0	4.5
PACIFIC	9.0	8.0	7.0
LATIN AMERICA	10.0	9.0	8.0
TOTAL	8.0	7.4	6.7

FIG. 4

FIG. 5

REVENUE PASSENGER MILES FLOWN IN INTERNATIONAL SERVICE BY U.S. CARRIERS

1973

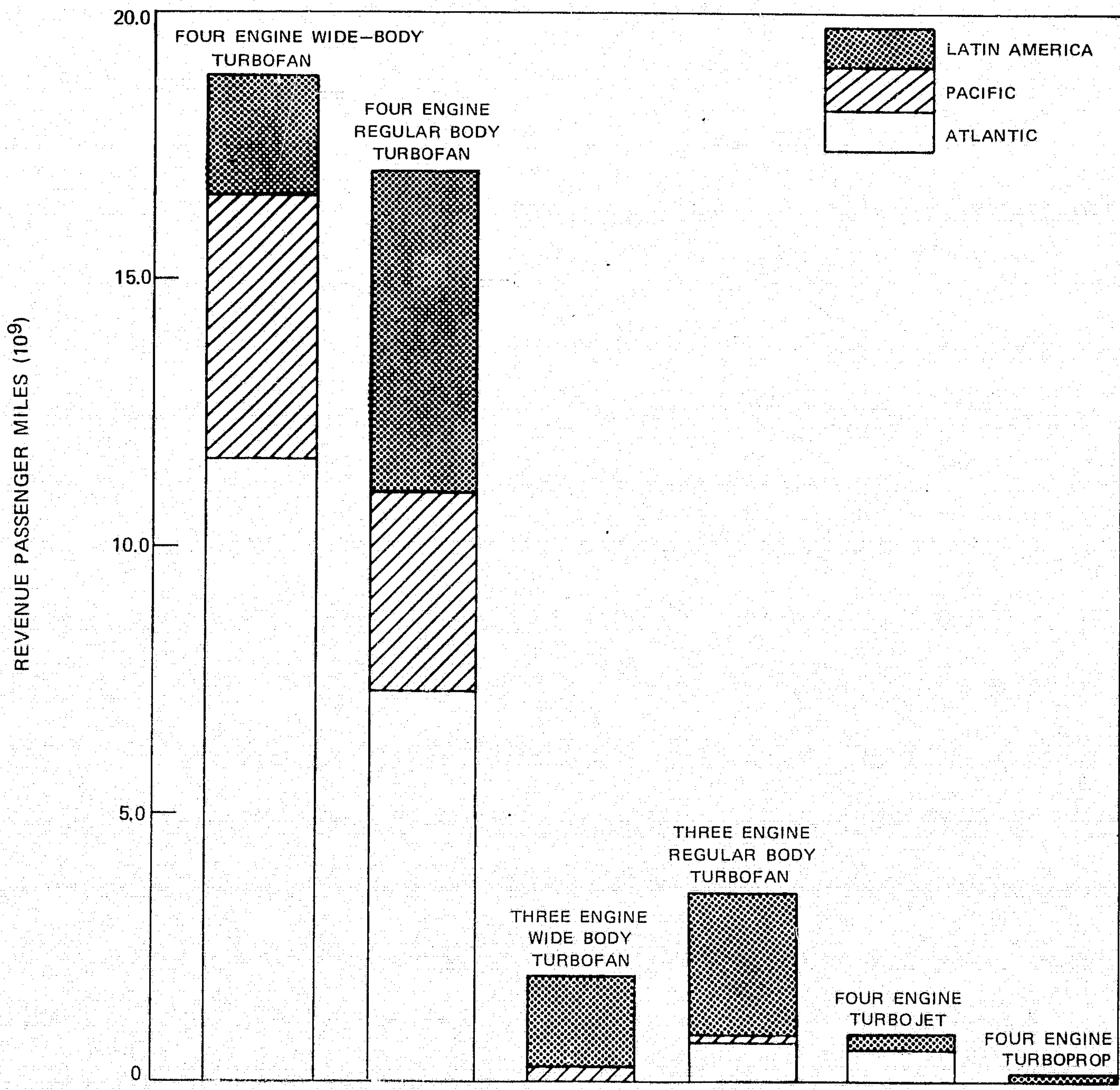


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FIG. 6

FUEL USED IN INTERNATIONAL PASSENGER 1973 SERVICE BY U.S. CARRIERS

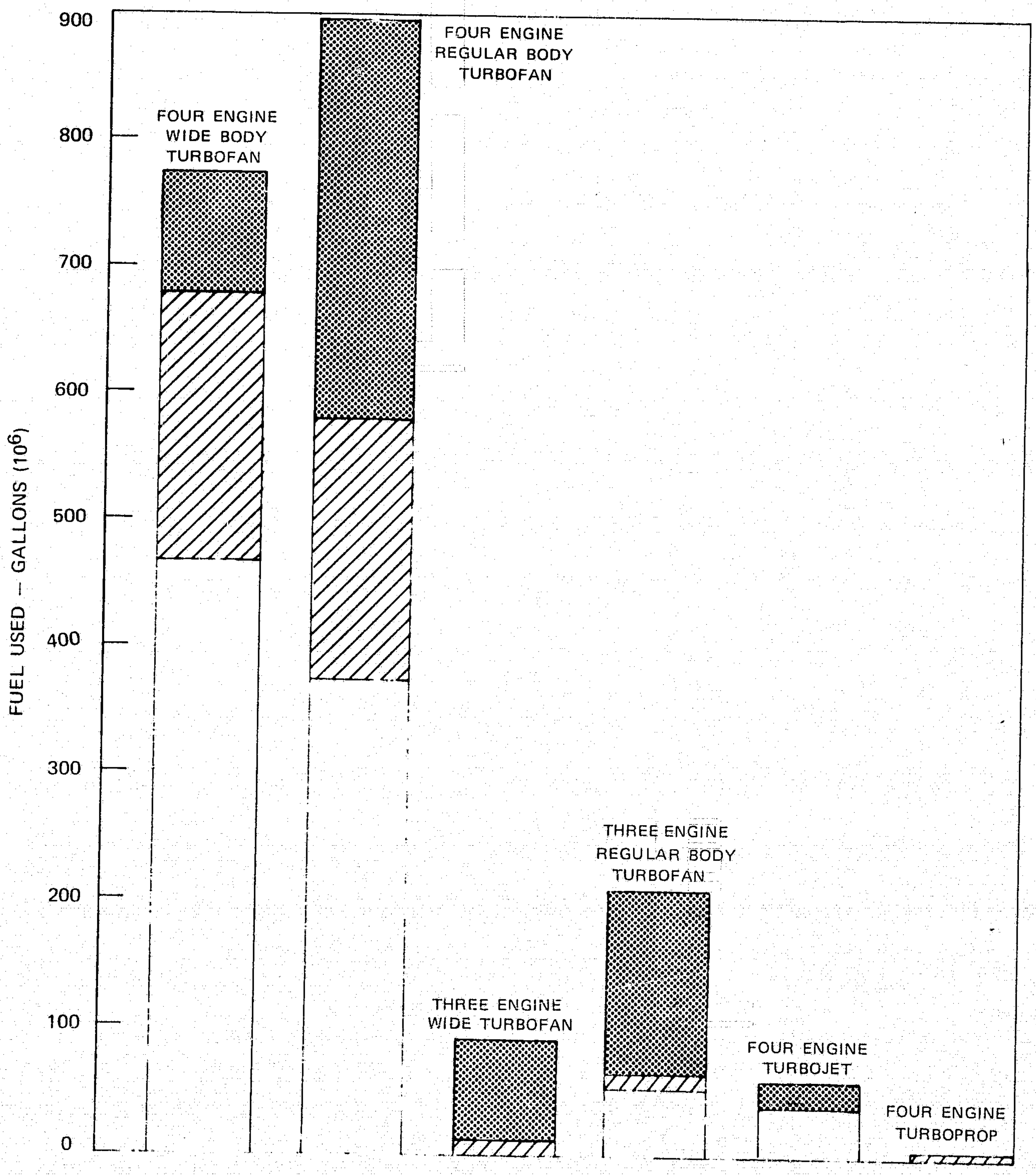

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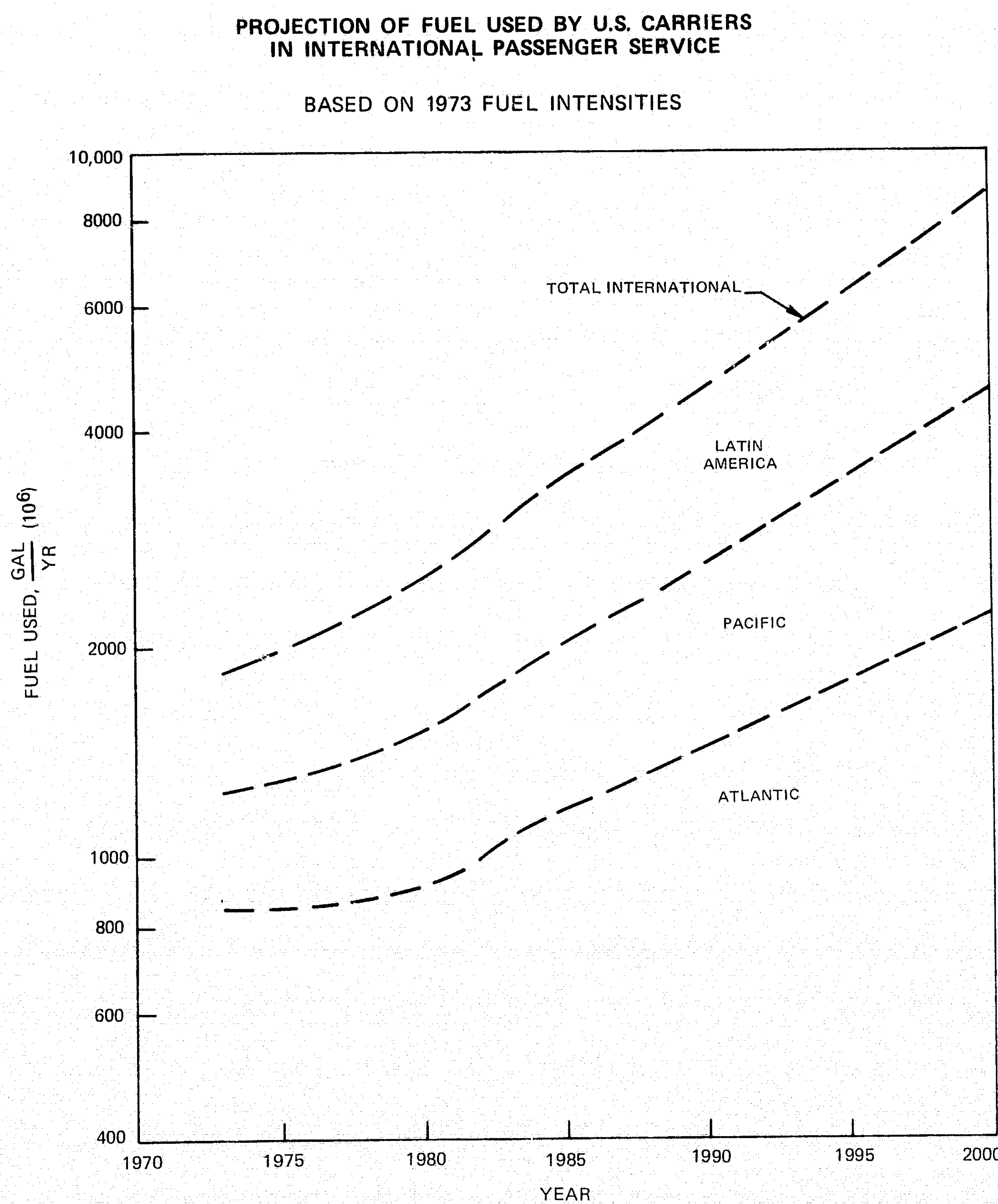
TABLE III

Summary of RPM and Fuel Projections

International Air Passenger Carriers

Zone	Type	73 RPM (10^6)	73 Gal (10^6)	80 RPM (10^6)	80 Gal (10^6)	85 RPM (10^6)	85 Gal (10^6)	90 RPM (10^6)	90 Gal (10^6)	95 RPM (10^6)	95 Gal (10^6)	100 RPM (10^6)	100 Gal (10^6)
Atlantic	4EWB	10,424	418	17,850	735	26,132	1077	34,056	1403	43,500	1792	53,600	2208
	4ERB	6,525	336	2,520	133	1,112	60	0	0	0	0	0	0
	3ERB	630	48	630	37	556	33	344	20	0	0	0	0
	4ETJ	547	36	0	0	0	0	0	0	0	0	0	0
	Total	18,126	838	21,000	905	27,800	1170	34,400	1423	43,500	1792	53,600	2208
Pacific	4EWB	4,440	191	11,647	480	16,660	686	23,630	974	33,150	1366	47,515	1958
	4ERB	3,339	185	1,946	102	784	41	0	0	0	0	0	0
	3EWB	212	10	437	20	2,156	99	4,170	191	5,850	268	8,385	384
	3ERB	81	9	71	4	0	0	0	0	0	0	0	0
	Total	8,071	394	14,100	606	19,600	826	27,800	1165	39,000	1634	55,900	2342
Latin America	4EWB	1,971	85	8,554	352	16,545	682	28,946	1193	42,028	1732	62,252	2565
	4ERB	5,389	282	3,960	208	3,110	164	0	0	0	0	0	0
	3EWB	1,572	71	4,118	188	8,335	381	14,564	666	24,472	1120	36,[illegible]48	1659
	3ERB	2,389	131	3,168	187	3,110	183	2,290	135	0	0	0	0
	4ETJ	257	18	0	0	0	0	0	0	0	0	0	0
	4ETP	66	4	0	0	0	0	0	0	0	0	0	0
	Total	11,643	591	19,800	935	31,100	1410	45,800	1994	66,500	2852	98,500	4224
TOTAL		37,840	1823	54,900	2446	78,500	3406	108,000	4582	149,000	6278	208,000	8774
Overall Fuel Intensity (gal/RPM)		0.04818		0.04456		0.04339		0.04243		0.04223		0.04219	

FIG. 7



PROJECTION OF FUEL USED BY U.S. CARRIERS IN INTERNATIONAL PASSENGER SERVICE
BASED ON 1973 FUEL INTENSITIES
TOTAL INTERNATIONAL
LATIN AMERICA
PACIFIC
ATLANTIC
FUEL USED, GAL/YR (10^6)
10,000
8000
6000
4000
2000
1000
800
600
400
1970
1975
1980
1985
1990
1995
2000
YEAR

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Summation of Fuel Usage

Using the scaling law derived earlier for domestic passenger-carrier fuel, the baseline 600 city-pair forecasts in Table VI*, the cargo fuel projection in Fig. 3, and the international fuel projection in Table III, an estimate can be made of anticipated fuel use by all U.S. certificated carriers. This summation is shown in Fig. 8. Since the growth rates are different in each of the three sectors, the percentage of total fuel used by domestic passenger carriers decreases from 75.8% in 1973 to 64.3% by the year 2000, while in the same period, cargo fuel use grows from 6.6% to 10.2%, and international fuel use from 17.6% to 25.5%.

Two qualifications should be noted with respect to Fig. 8. First, the slow growth in fuel use between 1973 and 1980 is related to the assumed seating density and load factor increases included in the RECAT ground rules (Table V*). Second, the fuel estimate for domestic passenger carriers is based on the detailed simulations described in the text, whereas the cargo and international projections are less credible in their derivation. However, since the derivation of cargo and international fuel data is well documented in the tables and figures of this appendix, variations in these projections can be easily incorporated into the results in Fig. 8.

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* Main text.

FIG. 8

FUEL USAGE BY US CERTIFICATED CARRIERS

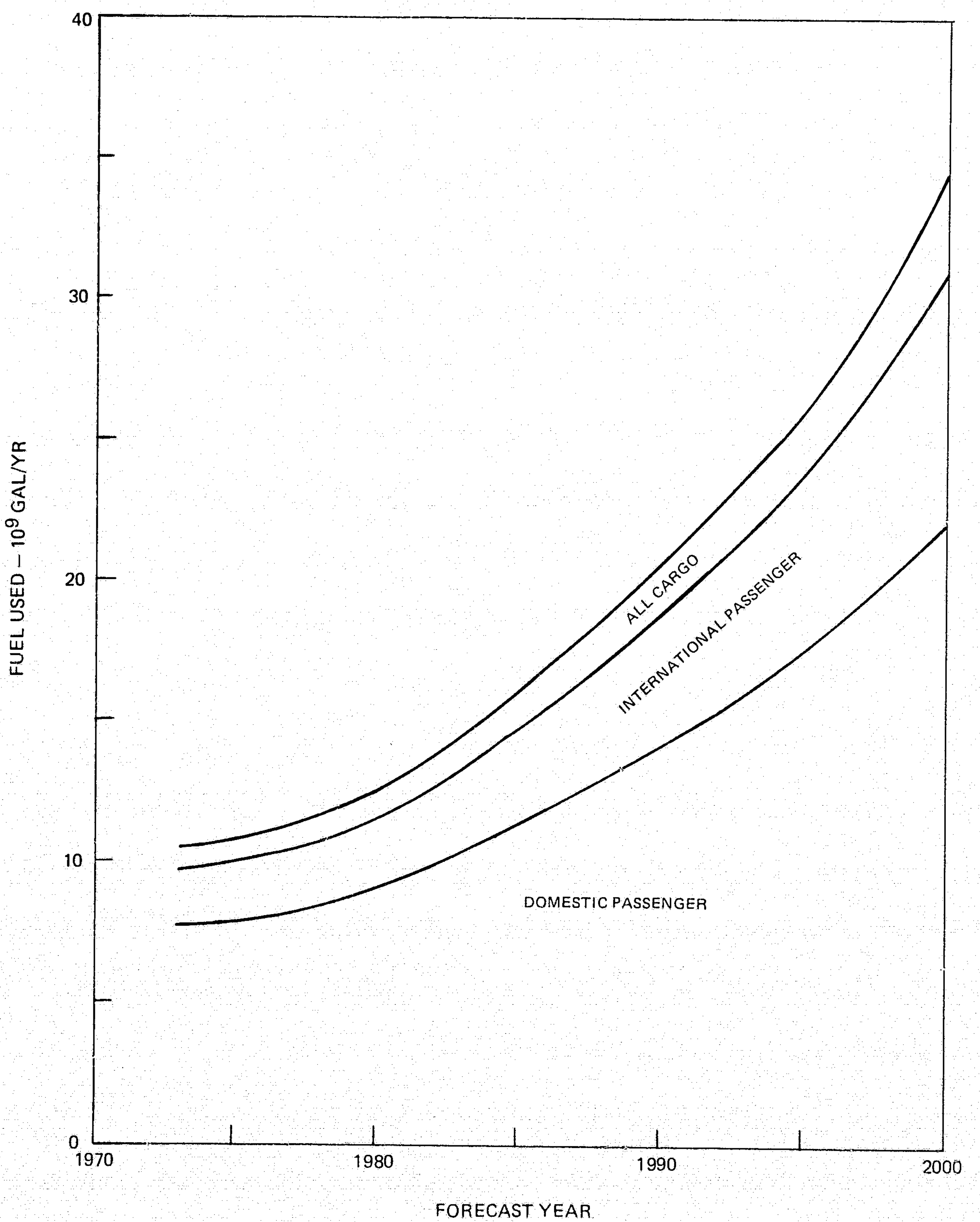

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TABLE III

Summary of RPM and Fuel Projections

International Air Passenger Carriers

Zone	Type	'73 RPM (10^6)	'73 Gal (10^6)	'80 RPM (10^6)	'80 Gal (10^6)	'85 RPM (10^6)	'85 Gal (10^6)	'90 RPM (10^6)	'90 Gal (10^6)	'95 RPM (10^6)	'95 Gal (10^6)	2000 RPM (10^6)	2000 Gal (10^6)
Atlantic	4EWB	10,424	418	17,850	735	26,132	1077	34,056	1403	43,500	1792	53,600	2208
	4ERB	6,525	336	2,520	133	1,112	60	0	0	0	0	0	0
	3ERB	630	48	630	37	556	33	344	20	0	0	0	0
	4ETJ	547	36	0	0	0	0	0	0	0	0	0	0
	Total	18,126	838	21,000	905	27,800	1170	34,400	1423	43,500	1792	53,600	2208
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	4ERB	3,339	185	1,946	102	784	41	0	0	0	0	0	0
	3EWB	212	10	437	20	2,156	99	4,170	191	5,850	268	8,385	384
	3ERB	81	9	71	4	0	0	0	0	0	0	0	0
	Total	8,071	394	14,100	606	19,600	826	27,800	1165	39,000	1634	55,900	2342
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	3ERB	2,389	131	3,168	187	3,110	183	2,290	135	0	0	0	0
	4ETJ	257	18	0	0	0	0	0	0	0	0	0	0
	4ETP	66	4	0	0	0	0	0	0	0	0	0	0
	Total	11,643	591	19,800	935	31,100	1410	45,800	1994	66,500	2852	98,500	4224
TOTAL		37,840	1823	54,900	2446	78,500	3406	108,000	4582	149,000	6278	208,000	8774
Overall Fuel Intensity	(gal/RPM)	0.04818		0.04456		0.04339		0.04243		0.04223		0.04219	

APPENDIX B

DERIVATION OF NEW FAR-TERM TURBOFAN AIRCRAFT

The task described in this appendix concerns the derivation of new, far-term, fuel-conserving airplanes from the Boeing study, "Fuel Conservation Possibilities for Terminal Area Compatible Aircraft" (Ref. 9). The Terminal Area Compatible Aircraft (TAC), as a generic type, uses composite material in the primary structure, advanced-technology engines, stability augmentation, and a high-aspect ratio wing with supercritical airfoil sections. In addition, the TAC airplane includes the following features to improve its fuel consumption and reduce the delay time associated with terminal area operations:

- Trailing-edge flap scheduling to minimize vortex strength and permit one- to three-mile separations on approach

- Adequate takeoff thrust to achieve an 8- to 10-deg takeoff gradient, and a high-aspect ratio (12) wing with 25-deg sweep. The TAC airplane has improved low-speed aerodynamics, low noise, and uses less fuel in takeoff than a conventional aircraft.

- Rapid deceleration on the ground combined with a high-speed turnoff capability to reduce runway occupancy on landing

- Powered wheels to allow terminal area compatibility without the need for towing

In this study, some of the benefits made possible by these terminal-area-compatible features cannot be achieved because they require system changes (ATC and aircraft-based equipment) which are not assumed as nominal. Therefore, the object being to define an advanced airplane which will conserve fuel independently of overall system improvements, changes were made to the TAC airplane as described below. In addition, scaled-up versions were defined (357 and 512 seats, compared with 201) to provide some flexibility in the fleet assignment process. The characteristics of these aircraft are summarized in the table below:

CHARACTERISTICS OF NEW, FAR-TERM TURBOFAN AIRCRAFT

Designation	N85-200	N85-350	N85-500
Range (nmi)	3,000	3,000	3,000
Cruise Mach No.	0.8	0.8	0.8
Takeoff Field Length (ft)	8,300	8,300	8,300
Capacity with 10/90 Split (seats)	201	357	512
Gross Weight (lb)	254,200	432,100	528,700
Initial Cost with Spares (1973 $)	16.56×10^6	29.00×10^6	35.31×10^6
Engines:			
Number	4	4	4
BPR	6	6	6
SL Static Thrust (lb)	15,200	24,600	29,500

Performance and Economic Characteristics

Block Time

The Boeing estimate for block time incorporated TAC time-saving features which are not consistent with the RECAT study. Therefore, Boeing's estimate was increased by nine minutes to be compatible with the expected level of ATC delays postulated for the mix of airplanes in the study. The resulting block time equation is

$$t_B = \begin{Bmatrix} 0.45 \\ 0.56 \\ 0.59 \end{Bmatrix} + \frac{R}{529} \quad , \quad \text{Hour} \tag{1}$$

where R is in st. mi., and the numbers in brackets refer to 201-, 357-, and 512-seat aircraft, respectively.

Block Fuel

The only adjustment made to block fuel was an allowance for the additional delay time implicit in Eq. (1). At a load factor of 58 percent, the block fuel is given by Eq. (2).

$$\text{Fuel} = \begin{Bmatrix} 580 \\ 960 \\ 1140 \end{Bmatrix} + \begin{Bmatrix} 1.97 \\ 2.99 \\ 3.57 \end{Bmatrix} R, \text{ Gal} \tag{2}$$

Operating Cost

The total operating cost of this airplane was estimated based on a modified 1967 ATA equation, for the DOC, and the Lockheed IOC method using 1973 coefficients. The crew cost in the ATA method was increased by 42 percent to be compatible with assumptions being used by the other RECAT contractors, giving $210 per block hour compared with a Boeing estimate of $275 per flight hour. Other DOC assumptions are listed below:

- Depreciation - 16 years with 10 percent residual values
- Spares - 15 percent of airplane first cost
- Insurance rate - 1 percent of first cost per year
- Maintenance Labor Rate - $6.10 per hour
  60 percent of the ATA cost per cycle
  75 percent of the ATA cost per hour
- Maintenace burden - 1.8 times the direct airplane and engine labor costs
- Utilization - 9 hours per day (assumed constant)

The resulting total operating cost less fuel is given in Eq. (3).

$$TOC_{Less\ Fuel} = \begin{Bmatrix} 1153 \\ 1753 \\ 2136 \end{Bmatrix} + \frac{\begin{Bmatrix} 1576 \\ 2659 \\ 3756 \end{Bmatrix}}{t_B} \quad , \$/\text{Block-Hr} \qquad (3)$$

APPENDIX C

DEMAND AND MODAL SPLIT MODELS*

Summary

An innovative transportation demand forecasting method is presented which is particularly suited to the analysis of the impact, on travel demand, either of new modes or of changes to existing modes. The approach consists of two distinct but related steps. First, the total demand for travel between two cities is forecasted; this demand is then divided among the competing modes through the use of a modal-split model. Both calculations are sensitive to the characteristics of the transportation system being analyzed. The paper discusses the derivation, calibration, and application of the two models.

Modal-Split Model

Theoretical Background

The modal-split model divides the total demand for transportation between two cities among the competing modes based on the total travel cost of each mode to the user. This total cost, referred to as disutility, includes money costs, travel time, and measures of inconvenience combined into a single quantity by means of a value of time. In an ideal situation, with all travelers evaluating the disutilities of two competing modes, D_a and D_b, identically, and basing their decisions solely on disutility, the modal split would appear as in Fig. 1, all travelers choosing the mode with the lower disutility. In reality, however, each traveler will perceive the situation differently and the disutilities calculated by the analyst will represent average values at best. Consequently, the actual modal split will be as shown in Fig. 2, a probabilistic distribution based on the relative values of the modal disutilities.

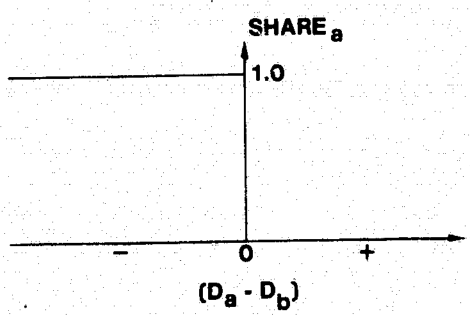

FIG. 1 Ideal modal split.

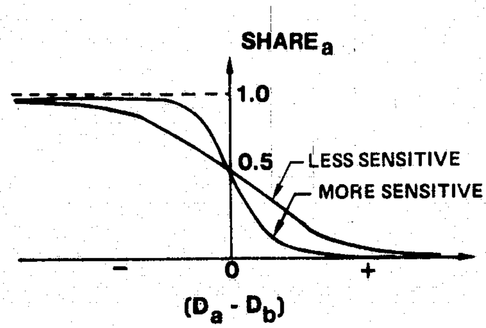

FIG. 2 Actual modal split.

Formalization of the modal-split model and extension to multiple-mode scenarios require that the disutilities be normalized in some way, preferably to an appropriate mean. After some experimentation it was concluded that this can best be done with a harmonic mean defined for the n-mode case as

$$\frac{1}{\bar{D}^2} = \sum_{i=1}^{n} \frac{1}{D_i^2}$$

where D_i is the disutility of the i^{th} mode. The harmonic mean represents the overall disutility of travel, considering all modes. It is always less than the lowest modal disutility, but is very near the lowest disutility if all the other disutilities are much higher. Without the exponent, it is analogous to the overall electrical impedance of several impedances in parallel, an apt analogy since the traveler ("current") can choose any one mode ("impedance") to complete his journey. The exponent of 2.0 was found to improve the model correlation by keeping the harmonic mean closer to the lowest disutility. The modal-split model gives the modal share of mode k as

$$S_k = \frac{\Phi\left(A\frac{\bar{D}_k - D_k}{\bar{D}}\right)}{\sum_{j=1}^{n}\left[\Phi\left(A\frac{\bar{D}_j - D_j}{\bar{D}}\right)\right]}$$

where $\Phi(x)$ is the cumulative area under the normal distribution curve, given by

$$\Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy$$

and

$$\frac{1}{\bar{D}_k^2} = \sum_{\substack{i=1 \\ (i \neq k)}}^{n} \frac{1}{D_i^2}$$

(i.e., the harmonic mean of all modes competing with k). The parameter A is a sensitivity coefficient

*Based on technical paper, Ref. 25

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determined by regression analysis; its effect on the modal split is shown qualitatively in Fig. 2. High values of A result in modal splits more sensitive to disutility differences, in the limit approximating the ideal modal split. Low values of A are characteristic of less sensitive modal splits; a value of zero would indicate a completely random modal split independent of disutility -- a horizontal line passing through the 0.5 share ordinate.

The above modal-split model can be classified as an aggregate model since the modal shares are determined by one calculation involving the average traveler (i.e., all the travelers are aggregated together for the purpose of determing the modal split). In models which employ a disaggregate approach, travelers are divided into groups by trip purpose, income level, travel party size, etc., and a separate modal split is determined for each group. Since disaggregate models require substantial data both for calibration and forecasting, as well as more computation, the aggregate model appears more practical. However, one step toward disaggregation has been taken with the use of separate modal splits for business and personal travelers. There are three reasons for this breakdown: (1) the dissimilarities between business and personal travelers are greater than for any other traveler subgroup; (2) sufficient data for calibration and forecasting are available, as described below; and (3) this type of disaggregation is often desired by users of transportation forecasting models.

Definition and Computation of Disutility

Disutility, the basis for the modal-split computation, is defined as

(trip time) + (trip cost)/(value of time)

and represents the total time of the trip including the time-equivalent of the trip cost. (In earlier versions of the model, disutility was measured in dollars (cost + time x value of time). The formulation was changed for compatibility with the demand model, as described later, but the change does not affect the modal-split model.) Disutility, in hours, is computed on a per-traveler basis for a one-way trip. Components of trip time include intercity travel time, local access/egress and terminal time, and the time-equivalent of schedule inconvenience. Trip costs include intercity fare, local access/egress and terminal costs, enroute meal and lodging costs, and the cost of local transportation at the destination. Definition and computation of each disutility component are described below.

Intercity travel time is the terminal-to-terminal time, for public modes, or average door-to-door driving time, for auto. Times can be taken directly from schedules for existing modes or calculated for new modes. In the case of auto, nonstop driving times taken from tables often found in highway atlases are increased by 10 percent to allow for fuel, meal, and rest stops.

Local access/egress and terminal times and costs represent the time and cost of getting from the local origin to and through the terminals of public modes (and vice-versa at the destination).

Schedule inconvenience is converted to an equivalent time based on the assumption that the traveler's preferred departure time is independent of the service schedule. If the service frequency is high, the schedule inconvenience is one-half the average headway, or (8/F) for F departures spread over sixteen hours of operation per day. In a low-frequency situation, however, travelers will probably rearrange their affairs to accommodate the schedule, and the perceived schedule inconvenience will be less than (8/F). Assuming that (1) the maximum schedule inconvenience is four hours for 1 or less departures/day, (2) 32 departures/day constitutes high-frequency service, and (3) schedule inconvenience is a continuous function, the schedule inconvenience time is given by:

$$t_{sched}(F) = \begin{cases} 4 & (F<1) \\ 4/F^{0.8} & (1<F<32) \\ 8/F & (F>32) \end{cases}$$

This function is shown in Fig. 3; it has been empirically verified as part of the modal-split model calibration.

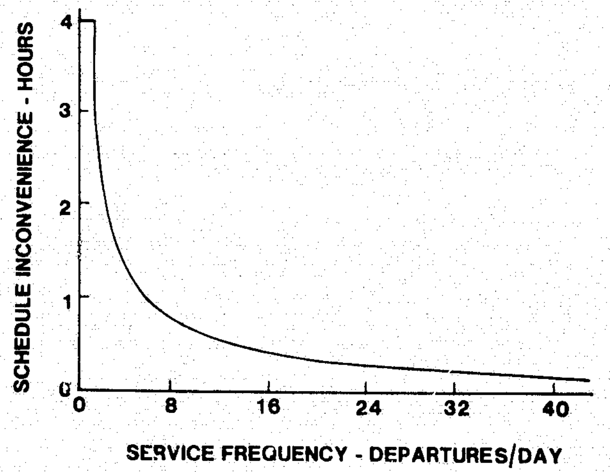

FIG. 3 Schedule inconvenience function.

Intercity fares can be taken from published data or calculated. Premium fares are not considered since the amenities purchased with the fare premium (wider seats, better meals, prestige) are difficult to quantify. In situations involving fare discounts, such as in the current air system, the average fare paid, rather than the published full fare, should be used; this results in different fares for business and personal travelers because of the more widespread use of discount fares for personal travel. For auto, the "fare" is the operating cost, plus tolls, divided by travel party size to apportion the total cost among those sharing the trip. Since intercity trips are not the major use of most automobiles, operating costs include only mileage-related costs (fuel, tire wear, repairs and maintenance), omitting fixed ownership costs such as depreciation and insurance.

Enroute meal and lodging costs account for the extra travel expenses associated with the longer periods away from home resulting from longer travel times. Although these costs are more significant for the slower modes, they are applied to all modes since any nonzero travel time increases the likelihood of extra expenses of this type. Even a two- or three-hour journey will cause some travelers to spend an extra night away from home, although the expenses may actually be incurred at the destination rather than "enroute". Meal and lodging costs are figured by converting the total travel time (including access time but excluding schedule inconvenience) into travel days or a fraction thereof, which is then multiplied by the meal and lodging cost per person per day. Because of their smaller travel party size, business travelers have higher (per person) lodging costs. For those modes offering complimentary meals, meal costs are arbitrarily halved.

Cost of local transportation at destination is included in the disutility of public modes because the auto traveler has his own car with him at his destination to provide convenient, low-cost transportation, while the public mode traveler does not. The cost of destination transportation is given by

$$C_{DT} = M_{DT} \times R_{DT} \times S_L/(2P_S),$$

where $M_{DT} = 1 - M_D \times D_D$. R_{DT} represents the daily rate for substitute transportation, which is generally independent of travel party size, P_S, and is therefore apportioned among the travel party members; S_L represents the length of stay at the destination in days; the factor 2 is introduced to apply half of the total cost to each one-way leg of the round trip, since the total cost is incurred only once during a round trip; and M_{DT} represents an adjustment multiple based on the density of the destination city, D_D, expressed in 10^3 persons/mi^2. The form of M_{DT} reflects the observation that the relative cost of not having one's own car for local travel decreases as the destination density increases, probably because public transportation is more plentiful and local travel distances are shorter. In the extreme (New York), congestion and high parking fees would make a car a relative burden, resulting in a zero or negative value for M_{DT}. (A negative cost of destination transportation represents an advantage for public-mode travelers relative to auto travelers, just as a positive value indicates a relative disadvantage.) The density multiple M_D is determined in the model calibration described below. The daily rate R_{DT} can represent the actual cost of car rental, taxis, etc. or can represent the abstract inconvenience of not having one's own car. In practice, R_{DT} is based on rental car costs. Since the daily cost of renting a car generally declines with the rental period, R_{DT} is a function of S_L derived from an analysis of car rental schedules. R_{DT} is calculated assuming that the car is driven 100 miles per day and crediting the rental charge with the cost of operating the traveler's own car this distance (i.e., C_{DT} represents the extra cost incurred by not having one's own car at the destination.

Model Calibration

The data source for the modal-split model calibration is the 1972 National Travel Survey (NTS)[1]. This is is a survey of intercity (i.e., 67 straight-line miles (108 km) or more) travel conducted at about five-year intervals by the U.S. Census Bureau; in 1972, 24,000 households were surveyed and information on 75,000 trips obtained. Pertinent data for each trip are stored as a separate data record on a public-use computer tape, a copy of which was purchased and processed for this study. Two of the data elements in each record are the trip's origin and destination cities or Standard Metropolitan Statistical Areas (SMSA). (All trip records are for round trips, with the origin being the traveler's residence and the destination being the farthest point on the trip's itinerary.) It is thus possible to extract data for specific city-pairs. The amount of such data is limited, however, by the fact that many trip origins and/or destinations lie outside SMSA's. Furthermore, the Census Bureau suppresses such data unless the specific origin or destination SMSA appeared in 400 or more records; thus, only 29 origin and 26 destination SMSA's, out of a total of 247, are specifically identified. Twenty-two cities appear as both origins and destinations, 7 as origins only, and 4 as destinations only; a total of 7964 records had both the origin and destination SMSA identified.

Twenty-five city-pairs were finally selected for inclusion in the calibration data base; each had at least 20 trip records reported by at least 10 different households in each travel category (business and personal). The total number of records for each city-pair varied from 51 to 383. Although in most cases the data cannot be considered a representative sample for each city-pair, it is assumed that a model calibrated against the behavior of a subset of travelers based on the specific characteristics for that subset will correctly predict the behavior of all travelers when provided with the appropriate general characteristics. As would be expected, 17 of the 25 city-pairs lie within the densely traveled Northeast and California corridors, and most of the rest are under 500 miles (800 km) apart.

The specific data extracted from the data tape for each city-pair included business/personal fractions of total travelers and separate values of average party size, length of stay at destination, air share, and value of time for business and for personal travelers. Value of time was calculated as follows:

(Annual Household Income/2080)/(Travel Party Size) for business travelers

(Annual Household Income/2080)/(Household Size) for personal travelers

The factor 2080 converts annual income into an hourly rate (52 forty-hour weeks). The use of travel party size for business travel in determining per-person income is appropriate since a principal wage earner is probably included in a business travel party. Since this is not necessarily true in the case of personal travel, income is apportioned among all the members of the household. Appropriate data describing the 1972 modal characteristics were also collected for these

city-pairs, including: air, bus, and rail fares; travel times, service frequencies, and access data; and auto driving times, distances, and tolls. All of this information was used to calculate disutilities, which were then used to calibrate the modal-split model against the air share data. (Only air shares were used because, in general, bus and rail shares are too small to be statistically reliable; as a result, the auto share is approximately (1 - air share) and is therefore redundant.) Overall air shares varied from 0 to 89.5 percent. Several of the assumptions and procedures used in the disutility calculation, as described above, were varied to test their correctness. The results are summarized below.

1) The determination of value of time described above was verified. Although a slight improvement in the model's accuracy was obtained when business values of time were increased, the improvement was not significant enough to justify values of time higher than those already used.

2) Values of M_D (multiple of destination-city density in the cost of destination transportation) of 0.050 for business travelers and 0.025 for personal travelers were obtained. The value of M_{DT} is thus +0.65 for Los Angeles and -0.32 for New York for business travelers; corresponding values for personal travelers are + 0.825 and +0.34. This difference indicates that business travelers are less inconvenienced by the lack of an automobile, particularly when traveling to relatively dense cities. A probable explanation is that business travelers are more likely to visit the central city area where public transportation is more convenient and one's own car is more likely to be a liability. To the extent that the local transportation cost biases the modal split towards auto, the higher value for personal travelers could serve as a surrogate for an unquantifiable preference for that mode.

3) Although the sensitivity coefficient for personal travelers tends to be higher than for business, equality can be forced with negligible loss of accuracy. A value of A = 1.60 was obtained, resulting in a standard error (σ) of 9.8 percent in the estimated air shares and a correlation coefficient (R^2) of 0.85.

When only two modes are involved, the modal-split model reduces to

$$S_1 = \Phi\left[A(1 - D_1/D_2)\sqrt{(D_2/D_1)^2 + 1}\right]$$

and

$$S_2 = 1-S_1.$$

The share of mode 1 as a function of the disutility ratio (D_1/D_2) is shown in Fig. 4. The modal split is fairly sensitive to this ratio; a 20 percent increase in (D_1/D_2) from 1.0 to 1.2 reduces the share of mode 1 from 50 percent to 34 percent, while a 20 percent decrease (to 0.8) increases the share to 70 percent.

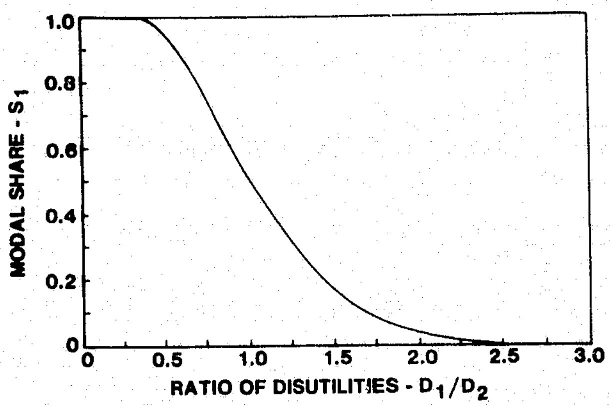

FIG. 4 Modal split for two modes (A=1.6).

Model Application

In order to apply the modal-split model, it is necessary to know various traveler characteristics for each city-pair, including travel party size, value of time, length of stay at destination for both business and personal travelers, and the overall business/personal fractions. Party size is needed to compute the per-traveler cost of local destination transportation, enroute lodging, and intercity auto "fare"; length of stay at destination is also required for the destination transportation cost; and the need for value of time is obvious. The business/personal fractions of total travel are used to combine the separate modal splits into an overall modal split for the city-pair. As indicated above, a sufficient quantity of data to determine these characteristics with statistical significance is available for very few city-pairs. Consequently, for most city-pairs it is necessary to use appropriate average values derived from analysis of the NTS data. Since forecasts are made for city-to-city travel, it was decided to include in the calculation of these average values only those NTS data records which indicate both origin and destination as being in an SMSA.

Travel Party Size. An analysis of these records showed that the average travel party size depended mainly on trip purpose; there appeared to be little, if any, correlation with trip distance or traveler income. The average party size, P_s, is 1.4 persons for business trips and 2.8 for personal.

Value of Time. The average value of time, computed as described above, was found to be \$2.11/hour for personal travelers and \$7.58/hour for business travelers. Since the average per-capita income for all SMSA's in 1971 (the time period reflected by the NTS income data) was \$4508/year, or \$2.17/hour based on 2080 hours/year, the value of time is about 1.0 times average income for personal travelers and 3.5 times average income for business travelers. These parameters are called value-of-time multiples and can be applied to the per-capita income of any particular SMSA, as forecasted for any year, to obtain appropriate values of time. The higher multiple for business travelers reflects both the different conversions between household income and value of time and the tendency for business travelers to have higher incomes than personal travelers.

The value of 1.0 for the personal traveler value-of-time multiple is not a definition but a coincidence. In actuality, those with higher incomes travel more, so that the average personal traveler has a higher income than the population in general. However, income data included in the NTS and reflected in the modal-split model calibration are as stated by the survey respondents, while income data and forecasts for SMSA's are computed by economists. The latter data include income which most people would not consider, such as employer-paid insurance and pension benefits and the potential income of owners' equity in their homes, and is thus higher than survey data. By coincidence, these two effects cancel each other, so that the average value of time for personal travelers is the same as the average per-capita income.

The effect of substantially higher values of time for business travelers is to make faster, higher-cost modes, such as air, more attractive to them relative to slower, lower-cost modes, such as auto. This is reinforced by the smaller party size for business travelers, which causes their per-person auto operating cost and enroute lodging cost to be higher, and by their lower perceived cost of not having a car at their destination. Thus, forecasted air shares are higher for business travelers than for personal travelers. The same phenomenon also occurs in the analysis of other fast, high-cost, modes, such as V/STOL or high-speed rail.

Length of Stay at Destination. The length of stay at destination (number of days) was found to depend upon both trip purpose and trip distance as shown in Fig. 5. Business trip lengths increase with distance to a maximum of 6.9 days for distances of more than 1300 miles (2090 km). Personal trip lengths reach a maximum of 14.6 days for distances of 2000 miles (3220 km) or more. The apparently excessive business length of stay probably results from the inclusion of only the major trip purpose in the National Travel Survey data. Many combination business/pleasure trips are reported as business trips (as indicated by the presence of family members in the travel party), thereby inflating the average business stay length when compared to trips whose sole purpose is business.

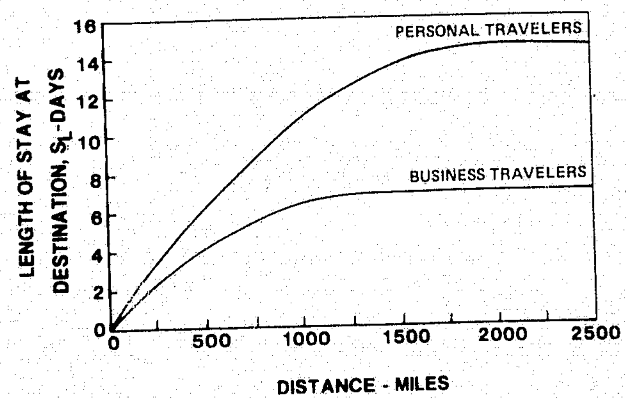

FIG. 5 Length of stay at destination.

Business Fraction. The business fraction of the total travelers for a particular city-pair was found to be a function of both distance and the cities involved. Since the business fraction varied so much from city-pair to city-pair, it was decided to incorporate data for specific city-pairs whenever possible. Thirteen of the 25 city-pairs used in the model validation were judged to have a sufficient number of records (100 or more) reported by a sufficient number of different households (35 or more) to provide meaningful business fractions. When data for these city-pairs were removed, it was found that the business fractions for the remaining city-pairs could be represented by

$$F_{B_{OD}} = 0.127\ d^{0.149} \times F_O \times F_D,$$

where d is the city-pair distance in statute miles, and F_O and F_D are origin and destination city correction factors. The uncorrected business fraction, $(F_{B_{OD}}/F_OF_D)$, is shown in Fig. 6. Note that $F_{B_{ij}} \neq F_{B_{ji}}$; consider, for example, New York - Miami. Similarly, $F_O \neq F_D$ for a particular city considered as both origin and destination. Sufficient data were available to calculate unique correction factors for 17 origins and 24 destinations, including 15 cities for which both F_O and F_D were calculated. All other values of F_O and F_D are unity. Values of F_O range from 0.86 (Cleveland) to 1.39 (Boston); and F_D from 0.30 (Honolulu) to 1.50 (Atlanta).

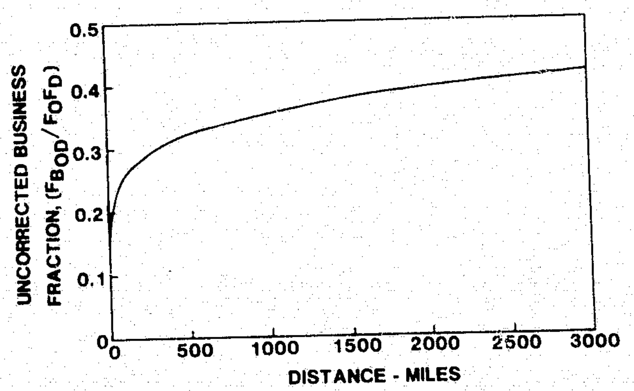

FIG. 6 Uncorrected business fraction of total travelers.

It is apparent that the disutility computation for a traveler having origin i and destination j (i.e., an i-j-i round-trip traveler) is different than the disutility for a j-to-i traveler (i.e., j-i-j round trip). There are three differences: (1) the origin city average income used in computing the values of time; (2) the destination city density term in the cost of destination transportation; and (3) the business fraction correction factors. Thus, there is a total of four sets of disutilities and four modal splits for each city-pair (business and personal for each direction). The overall city-pair demand for a particular mode is found by combining the business

and personal modal shares for one direction into an overall share and then applying this share to the directional demand. (See the following discussion of the demand model.) The overall share of mode i is given by

$$S_i = F_B S_{B_i} + (1 - F_B)\, S_{P_i},$$

where S_{B_i} and S_{P_i} are the shares of the business and personal travelers selecting mode i, and F_B is the business fraction of the total travelers. This process is then repeated for the other direction and the two directional modal demands are added together. Another consideration in disutility computation is that traveler characteristics for the city-pair as a whole are used rather than those for a specific mode. Thus, for example, the same party size is used in computing the disutilities for all modes, even though the travelers choosing auto will tend to have larger party sizes. This equivalent size is used so that all modes will be evaluated on a common basis with respect to the average traveler.

Reliance on traveler characteristics extracted from the 1972 NTS for forecasting future years naturally leads to the question of whether these characteristics change with time. Data from the other three National Travel Surveys -- 1957[2], 1963[3], and 1967[4] -- were analyzed in an attempt to answer this question. Unfortunately, the four surveys are not strictly comparable since each used different definitions, questionnaire phrasing, and sampling methods. Since the older surveys are available only in summary report form, it is not generally possible to extract consistently defined data.

Data for size of the average travel party (business and personal), business traveler fraction, and length of stay at destination from the four surveys were compared. The travel party sizes and business fractions were virtually identical after adjustment for inconsistent definitions. Length of stay at destination did show a moderate decline in the 1957-1972 period; however, it is not clear that the trend can be extrapolated into the future. Furthermore, the available data are for all travel; data for travel between SMSA's are available only for 1972. In summary, there are insufficient data to forecast future values of the traveler characteristics used in the modal-split model. Since the 1972 data are the best available, and since there is no indication of substantial variations over a fifteen-year period, it is reasonable to use 1972 values in forecasting future years.

Demand Model

Theoretical Background

The demand model forecasts the total (i.e., via all modes) demand for transportation between two cities. Many attempts to predict travel demand between two points have evolved from analogy to the expression for the gravitational attraction between two bodies. In the transportation demand analogy, populations of the interacting cities are analogous to the masses of attracting bodies, and the distance is taken as the impedance to travel. Thus, the classical "gravity" model for travel demand Q_{ij} is:

$$Q_{ij} = \frac{K\, P_i\, P_j}{d^{\alpha}}$$

where Q_{ij} is the number of travelers per year between cities i and j, P_i and P_j are the populations, and d is the distance between the cities. K and α are empirical constants determined from regression analyses of historical data. In the transportation context it is not necessary that the exponents of P_i and P_j should be unity, and it is clear that, if P_i and P_j are used to represent the potential for travel interactions, some situations will require a representation of this potential by factors other than the population itself.

One might expect that the gravity model would yield a reasonably consistent representation of total demand in a relatively homogeneous medium such as the domestic United States. However, in most cases where analysts have tested for coefficient repeatability, they have been disturbed by the instability of the coefficient K. That is, this coefficient as derived from regression analyses of historical data is very volatile in its value with respect to the choice of data points selected. This coefficient instability of the classical gravity model leads one to suspect the validity of the model. A clear illustration of this coefficient instability is an order-of-magnitude discrepancy between the regression lines for travel demand in the California Corridor in 1960 and the Northeast Corridor in the same year[5]. Conceivably this could be caused by differing per-capita travel habits. However, an examination of the statistics in various U.S. Travel Surveys indicates that the per-capita travel levels in California are only about 50 percent higher than in the Northeast.

The reason for this discrepancy, which was first postulated and later validated, appears to be related to the number of travel choices available. Given a reasonably constant propensity to travel, as noted above, the trip demand between two centers having a given travel attraction (product of populations) will vary depending on the number of alternatives available. As a result of the availability of many other trip opportunities (other cities), travel between two cities in a dense region will be much less than the travel between two other cities (having the same travel propensity as measured by population and distance) in a sparsely settled region.

Thus, the simple gravity model, as stated, will not be generally true, but an improved "n-body" gravity model can be derived from it. To do this, it is assumed that the basic gravity model, while incapable of measuring the absolute level of demand for a city-pair, can be used to measure the relative level of demand. Thus, the fraction of the total trips originating in city i which is attracted to city j is given by

$$F_{ij} = \frac{Q_{ij}}{\sum_k Q_{ik}} = \frac{C A_{ij}\, P_i^{a}\, P_j^{b} / D_{ij}^{c}}{\sum_k \left(C A_{ik}\, P_i^{a}\, P_k^{b} / D_{ik}^{c} \right)} = \frac{A_{ij}\, P_j^{b} / D_{ij}^{c}}{\sum_k \left(A_{ik}\, P_k^{b} / D_{ik}^{c} \right)}, \quad (1)$$

where the form of both the numerator and denominator (summation) is analogous to the gravity model. The summation in the denominator is called the n-body term and represents the demand dilution due to alternative destinations. In practice, it includes all cities among the 247 SMSA's defined by the Census Bureau which are more than 67 miles (108 km) from the origin. This minimum distance defines intercity travel in the 1972 U.S. Travel Survey[1] and is used to eliminate from consideration commuter-like travel between very close city-pairs such as Baltimore-Washington and New York-Newark. An attraction factor A_{ij}, unique to each city-pair is used to quantify the non-population characteristics of city j which attract travelers from city i; it is especially important for destinations such as Miami and Las Vegas. When attraction factors are used, the model coefficients need not account for large city-pair to city-pair variations in demand, thereby improving the accuracy of the model for more typical situations. In the above expression, distance has been replaced by disutility, D_{ij}, which is a more accurate measure of impedance to travel. The disutility term, D_{ij}, is calculated in the modal-split computation and is the harmonic mean of the disutilities of the competing modes. Since two harmonic means are calculated for each city-pair (for business and personal travelers) an average value weighted by the business/personal traveler fractions is used in the demand model. The exponents b and c are universal constants to be determined by regression analysis to historical data.

Completion of the demand model derivation requires an expression for the total number of trips to all destinations originating in city i. This demand is postulated to be

$$\sum_k Q_{ik} = \frac{K\, P_i^{\,a}}{\bar{D}_i^{\,d}} \tag{2}$$

where K, a, and d are universal constant determined via regression analysis. The average disutility of a trip originating in city i is $\bar{D}_i$, which is given by

$$\bar{D}_i^{\,d} = \frac{\sum_k \left(Q_{ik}\, D_{ik}^{\,d}\right)}{\sum_k Q_{ik}} \tag{3}$$

From Eq. (1), the above definition can be rewritten as

$$\bar{D}_i^{\,d} = \frac{\sum_k \left(A_{ik}\, P_k^{\,b}/D_{ik}^{\,c-d}\right)}{\sum_k \left(A_{ik}\, P_k^{\,b}/D_{ik}^{\,c}\right)} \tag{4}$$

which is more readily computed. The average disutility term, $\bar{D}_i$, causes the total demand to be sensitive to changes in the overall disutility of travel. System-wide changes, such as a change in the air fare structure, will affect the total level of travel. On the other hand, a disutility change affecting only one city-pair (i.e., a change in D_{ij}), while having a minimal impact on $\bar{D}_i$ and hence on total demand, will alter the distribution of the demand, as shown by Eq. (1). Although income does not explicitly appear in Eq. (2), it is a component of disutility; hence, an increase in income levels will reduce the average disutility (by reducing the time-equivalent of the trip cost), thereby resulting in an increase in total travel. Because of this effect, an income term in the total demand expression is unnecessary; also, the relatively high correlation between population and per-capita income can cause statistical difficulties when explicitly including income.

The final form of the demand model is found by combining Eqs. (1), (2), and (4),

$$Q_{ij} = \frac{K\, P_i^{\,a}}{\bar{D}_i^{\,d}}\; \frac{A_{ij}\, P_j^{\,b}/D_{ij}^{\,c}}{\sum_k \left(A_{ik}\, P_k^{\,b}/D_{ik}^{\,c}\right)} \tag{5}$$

or

$$Q_{ij} = K\, P_i^{\,a}\; \frac{A_{ij}\, P_j^{\,b}/D_{ij}^{\,c}}{\sum_k \left(A_{ik}\, P_k^{\,b}/D_{ik}^{\,c-d}\right)} \tag{6}$$

The above expression gives the number of travelers originating in city i and having destinations in city j (i.e., i-j-i round trips). A completely analogous expression can be written for Q_{ji}, the number of j-i-j round trips. However, from the definition of attraction factors it is clear that A_{ji} does not necessarily equal A_{ij}; also, in the modal-split model discussion it was pointed out that D_{ji} does not equal D_{ij}. The total demand for travel between i and j, in terms of round-trip travelers, is given by

$$Q = Q_{ij} + Q_{ji}$$

The total flow of passengers is 2Q, since each round-trip traveler makes two one-way trips.

Model Calibration

Calibration of the demand model requires demand data for a reasonable number of city-pairs, preferably spanning several years. Auto demand data are generally unreliable and exist for only a limited number of short-haul markets. However, air demand data are both abundant and reliable due to the CAB's Origin-Destination Survey[6], which is based on a 10 percent sampling of all airline tickets. Consequently, it was decided to estimate total demand data by dividing air demand data by air shares as calculated by the modal-split model. Although this introduces errors into the data base, these are minimized in the case of long-haul city-pairs. Since long-haul air shares are known to be large, modal-split estimation errors have a relatively small effect on the total demand estimate. With this approach, total demand data were obtained for a much larger variety of distances, regions, and years than was previously possible.

The years selected for the demand model calibration were 1958, 1966, and 1972. These years span the transition from propeller to jet aircraft on domestic routes, a period marked by a large growth in air travel resulting from a substantial reduction in travel disutilities. By calibrating the model against a wide range of input data, its validity in making long-range future forecasts is enhanced. Also these three particular years lie close to the 1954-1974 growth trend line. The top ranked eighty-four city-pairs (by air passenger-miles) were selected; they range from 182 to 2716 miles (293 to 4373 km) in distance and had 1972 air demands varying from 28,000 to 2,800,000 round-trip travelers. Collectively they accounted for 46 percent of the total 1958 air passenger-miles and 37 percent of the air origin-destination travelers, declining to 32 percent and 31 percent, respectively, in 1972. Individual average, annual city-pair growth rates during the 1958-1972 period varied from 4 percent to 15 percent, compared to a domestic average of 10 percent. The demand model calibration data thus include a broad cross-section of the domestic travel market.

The modal characteristics for each city-pair were obtained for each year from appropriate issues of the Official Airline Guide, rail and bus schedules, highway atlases, etc.; the modal-split model was then used to calculate the disutilities and air shares.

As may be expected, calibration of an expression as complex as Eq. (6) is not straightforward. As a start, Eq. (6) is rewritten to simplify the right-hand side:

$$\left[\frac{Q_{ij}}{A_{ij}} \sum_k \left(A_{ik} P_k^{\,b}/D_{ik}^{\,c-d}\right)\right] = K\, P_i^{\,a}\, P_j^{\,b}/D_{ij}^{\,c} \qquad (7)$$

Assumed initial values of the attraction factors and the model parameters b, c, and d, along with air demand and population data and calculated disutilities and air shares, are used to compute the left side of Eq. (7). Taking the logarithm of each side of Eq. (7) permits the use of a standard multivariable linear regression computer program to compute those values of K, a, b, and c which minimize the standard error of the 252 data points (84 city-pairs for each of three years). Equation (7) can be rewritten to solve for A_{ij}; however, although there are two attraction factors for each city-pair, only the combined air demand is available. To obtain a unique solution, it is assumed that the attraction is either equal in both directions ($A_{ij} = A_{ji}$) or entirely unidirectional ($A_{ij} = 1$ or $A_{ji} = 1$). The former assumption is applicable for most city-pairs while the latter is applicable mainly when one city is a resort. Since attraction factors are obtained for each city-pair for each of three years, a geometric mean of the three values is computed for each city-pair. Using these new values of attraction factors and exponents, the left side of Eq. (7) can be re-evaluated and the entire process repeated; this is continued until the model coefficients converge, which usually requires no more than three or four complete cycles. Since the exponent d does not appear on the right side of Eq. (7), the entire regression analysis must be repeated for various values of d until satisfactory results are obtained.

Computation of the summation term in Eq. (5) or (7) requires knowledge of the attraction factor A_{ik} and travel disutility D_{ik} between the origin SMSA and all other SMSA's more than 67 miles (108 km) distant. Although these are known for some city-pairs, it is obviously impossible to collect all of the modal data necessary to calculate A_{ik} and D_{ik} for the remaining city-pairs. In these instances, A_{ik} is assumed to be unity while D_{ik} is estimated from nominal modal characteristics expressed as functions of distance.

The model coefficients determined from the calibration are: K = 1009; a = 0.90; b = 0.75; c = 1.15; and d = 1.85. The corresponding correlation coefficient (R^2) was 0.99 while the standard error of the 252 data point estimates was 15.6 percent. Aggregate errors (i.e., errors in estimating the total 84 city-pair air demand) were +0.8 percent, -1.4 percent, and +1.7 percent for 1958, 1966, and 1972, respectively. Overall aggregate error for all three years was +0.5 percent.

The very high correlation coefficient and very low aggregate errors indicate a good representation of the air demand data. Part of this is due to the existence of a separate attraction factor for each city-pair; however, since there are three data values for each city-pair (one for each year) and only one attraction factor, there are still modeling errors. The standard error is considerably higher than the aggregate error, indicating that the error in forecasting the total demand for a network of city-pairs is likely to be lower than the error for each individual city-pair.

The generality of the demand model was tested by significantly reducing the size of the calibration data base (either the number of city-pairs or the time span of the data) and recalibrating the model. The coefficients did not change significantly. This finding lends support to the application of the model to city-pairs and time periods beyond the calibration base.

As examples of the results obtained with the demand and modal-split models, data are presented in Table I for three important city-pairs taken from the demand model calibration data base. Washington-New York and New York-Los Angeles are, respectively, typical short- and long-distance higher density city-pairs, while San Francisco-Los Angeles is a unique situation chosen to illustrate the power of the models. The costs, disutilities, and air shares shown in Table I are averages for business and personal travelers. These averages were calculated specifically for this presentation; ordinarily, separate costs, disutilities, and modal shares are calculated for each travel purpose category, as explained in the discussion of the modal-split model. Between 1958 and 1972, the constant-dollar total cost of an air trip, reflecting changes in the air fare structure, rose for short trips and fell for long trips. In California, however, the introduction of low-cost, intrastate, air carrier service resulted in a sharp drop in air fare on the S.F.-L.A. route. In terms of total air time, the change from propeller to jet aircraft resulted in a substantial reduction on long routes, but only a modest reduction

TABLE I

DEMAND AND MODAL SPLIT MODEL RESULTS

	Washington - New York 1958	Washington - New York 1972	San Francisco-Los Angeles 1958	San Francisco-Los Angeles 1972	New York - Los Angeles 1958	New York - Los Angeles 1972
Distance - Miles (km)	206-(331)		335-(539)		2453-(3947)	
Total Air Cost* - 1970$	24	29	45	35	205	168
Total Air Time - Hours	3.2	2.9	4.5	3.2	11.5	8.2
Air Disutility - Hours	14.7	11.5	22.2	12.8	88.3	49.7
Mean Disutility - Hours	7.0	5.5	10.9	8.1	70.0	43.4
Air Share	28%	29%	26%	60%	78%	93%
$\bar{D}_i$ - Average Disutility - Hours	20.7	14.7	35.1	23.0	20.9	15.2
$\Sigma Q_{ik}/P_i$ - Trips/Capita	1.7	3.1	0.6	1.3	1.4	2.5
F_{ij}	0.165	0.142	0.457	0.435	0.007	0.010
Air Demand - 10^3 Round Trips - Estimated	342	783	420	2666	195	592
- Actual	357	620	498	2796	194	552

* Including fare, access, meals and lodging, and destination-transportation costs.

on short routes where access time is often greater than block time. In the case of S.F.-L.A., however, the introduction of service at satellite airports in both cities had a significant impact on access times, contributing to a sharp drop in total air time. The air times and costs are combined using the appropriate values of time which reflect income increases from 1958 to 1972, to obtain the air disutilities in Table I. Air disutility reductions for S.F.-L.A. (42 percent) and N.Y.-L.A. (44 percent) are more pronounced than for Wash.-N.Y. (22 percent) where rising air cost partially offset the drop in air time and the increase in value of time. The harmonic mean disutilities shown reflect the improvements in other modes -- faster auto and bus times, lower costs relative to income, Metroliner service for Wash.-N.Y., etc. Application of the modal-split model results in the air shares shown. In the case of Wash.-N.Y., air improvements are offset by improvements in the other modes, resulting in little change in the air share, a typical short-haul situation. On the other hand, a dramatic increase in air share occurs in the S.F.-L.A. market, where the greatly improved intrastate carrier service has made air the dominant mode. Although substantial air improvements also occurred for N.Y.-L.A., the effect of approaching saturation (i.e., modal shares can never exceed 100 percent) limits the increase in air share.

The average disutilities shown in Table I are for all trips originating in the first-named city of each pair; they reflect the modal improvements and income increases discussed above, showing about 30 percent decline from 1958 to 1972. The higher values for San Francisco, compared with Washington and New York, are consequences of the longer average travel distances prevalent outside the Northeast. The reduction in average disutilities results in the increase in travel propensities (trips per capita). It should be emphasized that the demand model is for SMSA-to-SMSA travel; therefore, the travel propensities shown are for travel to other SMSA's only. San Franciscans do not travel less, but many more of their trips are to non-SMSA destinations. The term F_{ij} represents the fraction of the total trips originating in city i which is attracted to city j. The three-fold difference in values between Wash.-N.Y. and S.F.-L.A. reflects the n-body effect; San Franciscans have few nearby SMSA travel alternatives and, as a result, a large proportion of their trips are attracted to Los Angeles. The decline in F_{ij} for the two short-haul situations is due to the fact that the changes in the air transportation system between 1958 and 1972 caused a larger decline in long-haul disutilities than in short-haul. As a result, a greater fraction of travel is attracted to more distant destinations, as indicated by the large relative increase in F_{ij} for N.Y.-L.A.

The combined results of the demand and modal-split models give the estimated air demands shown. Comparison with the actual data shows that the models have reproduced these three very different growth patterns quite well. The model estimates shown in Table I come directly from the demand model calibration and reflect attraction factors calculated from data for all three years. Thus, "forecasts" of 1972 based solely on 1958 attraction factors would show larger errors. Also, errors in modeling a future scenario (populations, incomes, modal characteristics) would result in forecasting errors not reflected in these examples.

The three examples presented in Table I display markedly different growth rates in air demand. The factors influencing the demand for travel via a specific mode in a particular market are discussed below.

Population, of both origin and destination cities, directly affects total demand through the demand model. Demand does not increase as rapidly as origin population (i.e., the exponent "a" is less than 1.0) because, in a larger city, intracity trips resemble short intercity trips in terms of disutility and because more of those needs which are potential causes of travel can be satisfied locally.

Income influences demand through disutility in three ways: (1) rise in income level will cause the average trip disutility ($\bar{D}_i$) of the origin SMSA to fall, thereby increasing the total amount of travel; (2) by lowering the time-equivalent of travel cost, an increase in income will increase the attractiveness of more expensive (longer) trips relative to less expensive (shorter) trips, causing a larger portion of total travel to be drawn to more distant destinations; and (3) within each city-pair the faster, more expensive modes (air, high speed rail) will become more attractive relative to the lower-cost, slower modes (auto, bus) when incomes rise, and their market shares will increase.

Modal characteristics influence demand through the same three mechanisms as income, since the two are combined to form disutility. Changing the modal characteristics for a particular city-pair will alter the modal split, directly affecting each mode's demand. Furthermore, the change in the mean disutility will make a particular destination more or less attractive relative to others, thereby increasing or decreasing the fraction of the origin's total travel (F_{ij}) attracted to it. Finally, a general change in the air or auto mode will cause the average trip disutility ($\bar{D}_i$) to change, stimulating or depressing the total level of travel.

Model Implementation and Application

Computer Program Structure and Usage

The modal-split and demand models form the basis of a large transportation simulation and forecasting computer program. This program has been applied to a number of corporate- and government-sponsored studies[7,8,9], including studies of VTOL, STOL, RTOL, and high-speed rail systems, and studies of the impact of possible future changes in the CTOL system. The following paragraphs describe the typical forecasting procedure.

1. Program construction. Various subroutines are compiled and assembled to form an executable program element. Included in the package are the SMSA populations and incomes for the specific years to be forecasted, which are automatically extracted from the SMSA data base. This data base contains population and income data for all SMSA's for a number of past years, as well as forecasts for future years prepared by the Bureau of Economic Analysis of the U.S. Commerce Department.[10] Also contained in the data base are density data for computation of the cost of destination transportation and longitude and latitude data used for intercity distance computation. Since several adjacent SMSA's sometimes share the same airport(s) and thus constitute a single air market, it is necessary to combine these individual SMSA's into a larger entity. Examples are New York/northeast New Jersey (4 SMSA's)/Fairfield County (Conn.); Los Angeles/Anaheim/Riverside; and San Francisco/San Jose.

2. Program initialization. Model parameters, the city-pair list, base-year modal data, and actual base-year demands (total or for a particular mode) are read from a specially prepared data file. Individual city-pair attraction factors are computed from the base-year data, as described in the section on the demand model. This involves computation of the disutilities and modal shares for the base-year followed by iterative use of the demand model until the errors between estimated and actual demand are sufficiently small. Since the attraction factors are valid as long as the base-year data are not changed, the attraction factors are saved for future reuse without recalculation.

3. Disutility and modal-split computation. The disutilities for each mode are computed for the first forecast year. Usually, baseline modal characteristics for each year are stored in data files and read prior to the disutility computations; only changes from the previous year are needed. Any deviations from the baseline required for a particular run are read separately after the baseline data. As discussed in the section on the modal-split model, the four sets of disutilities computed for each city-pair--one for each trip purpose (business, personal) and for each direction--form the basis for four modal splits. Using the business/personal traveler fractions, the two sets of modal shares and two harmonic mean disutilities for each direction are combined into average values. In cases where a mode is not available for all city-pairs (e.g., rail) or when its share would be negligible (e.g., bus or rail on long-haul routes), a mode can be omitted from the disutility and modal-split computations for the appropriate city-pairs.

4. Demand computation. The total demand is computed using the demand model and the mean disutilities from the modal-split computation. The n-body term, although requiring substantial computation, need only be calculated once for each individual city, regardless of the number of city-pairs in which that city appears. Application of the modal shares to the total demand gives the demand for each mode.

5. Mode adjustments. It is often desirable that modal characteristics reflect the demand for that mode. For example, service frequency can be matched to demand to give a reasonable load factor; fares can be adjusted to yield a specific return-on-investment; block times can be adjusted to reflect terminal congestion resulting from the frequencies required to serve the demand; etc. Once the characteristics of a mode have been changed, it is necessary to repeat steps 3 and 4 (disutility, modal-split, and demand computations) to account for the impact on demand. Thus, the forecasting process is iterative; steps 3, 4, and 5 are repeated until convergence, which usually requires between three and seven cycles. Once convergence has been reached and the forecast completed, new data are read for a new forecast year, or for a different scenario for the current year, and the entire process is repeated.

Although the forecasting procedure involves substantial computation, the amount of computer time

required is not excessive due, in part, to careful programming and the use of several computational shortcuts.

Model Application Considerations

Many modal-split models, including the UTRC model, are susceptible to the so-called "red bus/blue bus" problem. That is, when one mode is subdivided into two modes, the two components will have a combined share larger than the original mode. This occurs even if the division was made on an arbirtary basis such as vehicle color and despite the fact that the component modes have lower service frequencies, and therefore higher disutilities, than the original mode. This is not necessarily a weakness of the model, however. It could be argued that a new travel service would attract more travelers if it were perceived as a distinct modal choice rather than an addition to another mode. As a separate mode it would be considered by all travelers on the same basis as the other modes, while as part of an existing mode it would only be considered by those travelers who first selected that mode. Even though the new travel service would enhance the existing mode and increase its market share, the demand for the new service would probably be less than for a separate mode.

This phenomenon can cause difficulties in selecting the approach to be used in the analysis of new modes. For example, when a new air mode, such as VTOL, STOL, or RTOL, is introduced in a market already served by CTOL, it can be treated as a separate mode or as part of the air mode. In the former approach, a single-stage modal split is calculated for all modes (auto, bus, rail, CTOL, V/S/RTOL); in the latter, a four-mode modal split (auto, bus, rail, air) is followed by a two-mode split (CTOL, V/S/RTOL) of the air share, resulting in lower CTOL and V/S/RTOL shares. A third approach is to perform both the single-stage and two-stage modal splits and average the results. In past studies, either the two-stage or average method has been selected because they are more conservative; analysis as separate modes is probably appropriate only for truly new modes, radically different from any existing mode.

In the two-stage method, the characteristics of the composite mode (air) are synthesized from those of its components (V/S/RTOL and CTOL); service frequencies are added together while fares and block times are averaged, using frequency as a weighting. Special access values are used which consider all of the terminals of both modes, thereby resulting in access as good as or better than either component. The composite-mode disutility should be lower than either of the component disutilities because the composite mode offers additional travel choices beyond either component mode. The composite-mode disutility calculated as described in this way is usually lower than either component disutility, due to improved service frequency and access. Exceptions occur when one component has a high fare or block time relative to the other; in these instances the calculated disutility is replaced by the lower component-mode disutility.

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APPENDIX D

BENEFIT/COST ANALYSIS

Definition of Costs and Benefits

The usual costs associated with transportation are user costs (fare) and, occasionally, passenger time costs as quantified by a value of time. However, many other costs can be identified which may be referred to as "common costs."

Common costs include, of course, environmental and resource costs, where a prime example of the latter is energy consumption. Another common cost would be government spending not recovered in user fees. Common costs are viewed as being distinct from individually perceived costs inasmuch as it is expected that the vast majority of individual travelers will continue to make their decisions primarily on the basis of out-of-pocket costs, the time required to make the trip, and elements of personal convenience.

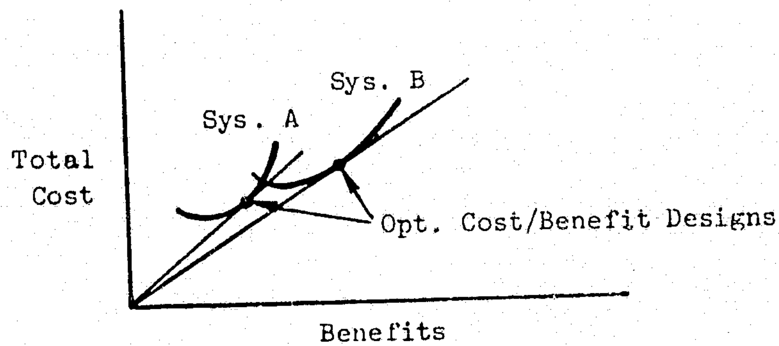
Common costs will be most strongly influential in the attitude of the public at large, including those elements of the public who do not travel often on specific modes such as air transportation, and who are anxious to protect their neighborhoods against change and eagerly look to newly found environmental and resource issues as allies in this concern. These common costs will be dominant in the consideration, by public bodies, of transportation alternatives (note the widespread requirements for environmental impact statements).

The usual benefit associated with transportation is passenger-miles served by the system. It is, in reality, a "common" benefit since the individual traveler rarely views the maximization of passenger miles as an individual benefit as long as his personal needs are served. Other common benefits could include employment provided by the transportation industry, contributions to a favorable trade balance, congestion relief in the public sector (notably at airports), auto-miles diverted from the highways as a means of reducing congestion and improving energy consumption, and the increase in land value and economic development which often results from the location of a new transportation system or expansion of an existing one. However, in the present study, only the prime common benefit -- passenger miles -- is considered.

Conceptual Evaluation

If all costs could be quantified to a common base, transportation modes, or systems, could be characterized by a single unit of cost (including common

costs) and alternative systems compared on the basis of least cost. If, furthermore, the "benefits" (including common benefits) of transportation systems could be quantified, a cost/benefit ratio could be used to add a further dimension in the comparison of alternative systems, and a comparative analysis could be illustrated as follows:



As shown, System A has lower total costs than System B and, in a suboptimized analysis, would be favored. But accounting for benefits as well as costs makes it possible to reveal a possible situation in which increased benefits compensate for increased costs such that System B, having a lower cost/benefit ratio, would be the favored system.

Unfortunately, it is difficult to quantify environmental and resource costs, and other common costs and benefits, in dollar units without making arbitrary assumptions which are open to question. The analyst is then subject to the charge that he has selected his dollar values so as to insure a favorable result for a preselected system.

Accordingly, UTRC developed a "fractionalized benefit/cost method" which involves the definition of "fractional" costs and benefits for modes or systems being compared, in order to avoid the problem of dissimilar units. For example, in the present study, a number of fuel-conserving options are being analyzed for overall merit. Each option is characterized by a calculable cost for each of several different types (user cost, user time, energy used, emissions generated, etc.), and each option is characterized by a different value for the transportation "benefit" (passenger-miles). A strict adherence to the benefit/cost methodology, as described in Ref. 14, would call for the formation of a fractional cost by dividing the cost for each option by the sum of the costs for all options, and similarly, for the formation of a fractional benefit by dividing the benefit for each option by the sum of the benefits for all options. Dividing the fractionalized benefits by the fractionalized costs then provides the benefit cost ratios which

would then be combined as discussed below.

However, since all fuel-conserving options in the present study are to be compared with the baseline, considerable simplification can be achieved by merely normalizing all benefit and cost values to those for the baseline. Thus, the normalized benefit, b_i, and the normalized costs, c_{ij}, are as follows:

$$b_i = B_i/B_o \quad \text{and} \quad c_{ij} = C_{ij}/C_{oj}$$

where B_i and C_{ij} represent a single benefit and the j^{th} cost associated with option i, and B_o and C_{oj} represent the corresponding baseline values. Fractional benefit/cost ratios, representing the amount of benefit provided per unit cost, relative to the baseline, are as follows:

$$f_{ij} = b_i/c_{ij}$$

A value of f_{ij} greater than 1.0 indicates that option i is superior to the baseline with respect to cost j (i.e., it provides more benefit per unit cost); a value less than 1.0 indicates the baseline is better.

For a system with only one type of cost and one benefit, the use of the simple benefit/cost ratio defined above provides the required evaluation. For a system with multiple costs ($j > 1$), the benefit/cost ratios individually evaluate, for each benefit-cost combination, alternative systems. However, in this case, the analysis is not completely definitive because a transport system may look good in terms of one benefit/cost ratio and bad in another; hence, a method is needed to estimate the relative importance of benefits and costs such that ratios can be combined to result in a composite rating.

Derivation of Weighting Factors

One way to approach this question is to ascertain how important each transportation cost is relative to all such costs. For example, how important is transportation air pollution relative to all sources of air pollution, or how much energy does transportation use relative to all energy consumption? If the transportation fraction of total air pollution is lower than the transportation fraction of total energy consumed, then the air pollution "cost" may be considered as less important than the energy "cost" and weightings assigned on the basis of these fractions. In this way, a series of cost weightings, ω_j, can be derived, where

$$\omega_j = \frac{\text{Transportation costs of type j}}{\text{All type-j costs}}$$

Such analytically derived weighting factors are theoretically free of bias on the part of the analyst but, when many costs are being considered, such weighting factors have only an incidental relationship to each other, and when compared among the number of costs being considered, the relative values may violate the analyst's judgement.

Because it has been found that bias tends to creep into the analytical process used for deriving weighting factors, it is possible that a purely judgmental process can yield meaningful values, individual bias being minimized by averaging judgmentally derived factors over a large number of raters. The value of this approach is that derived weightings may be more acceptable in relative terms, at least in a ranking sense, but has the disadvantage that proper separation of numerical values may not be achieved.

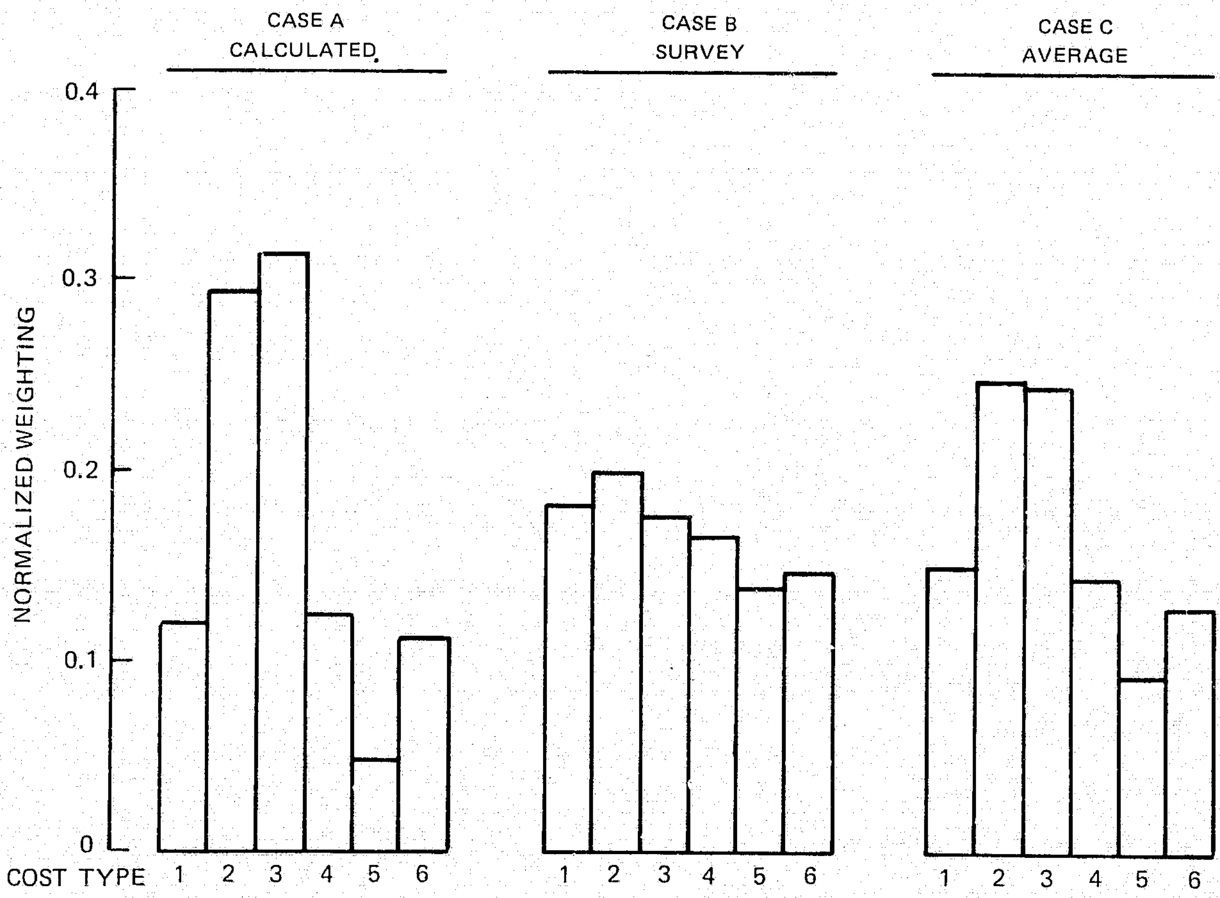
Accordingly, a survey of some 57 respondents was conducted to determine a set of weighting factors, based on pure judgement, which could be compared with the analytically-derived set described above. The normalized weighting factors derived in these two ways are summarized as Case A (calculated weightings) and Case B (survey weightings) in Fig. 1 for the specific costs considered in this study. The primary observation that emerges from a comparison of these two approaches is that all survey weightings fall within a fairly small band of numerical values (i.e., the highest (0.198) is only 45% greater than the lowest (0.137)), whereas the calculated weightings vary over a much wider range of values (the highest (0.311) is over six times the lowest (0.047)). It is thus apparent that the survey weightings will have relatively little impact as modifiers on individual benefit/cost ratios when combining them into benefit/cost ratings. A second observation is that the survey respondents perceive user time, user cost, and energy as being the most important, and in that order, whereas the calculated values indicate energy as being most important, with user time slightly less important, and emissions and user cost about equal and much less important than the first two costs.

In assessing the two techniques, the numerical significance of the calculated weightings is an appealing feature even though the individual costs bear only incidental relative significance. On the other hand, the survey weightings have an appealing relative significance, but the numerical quanities are strongly dependent on how the survey was made and provide little

COMPARISON OF COST WEIGHTING FACTORS

RANKING

COST TYPE	A	B	C
1. USER COST	4	2	3
2. TRAVEL TIME	2	1	1
3. ENERGY	1	3	2
4. EMISSIONS	3	4	4
5. GOV'T SPENDING	6	6	6
6. NOISE IMPACT	5	5	5



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separation among costs. Inasmuch as there is no straightforward way of deciding on which technique is better, a simple-minded (and very arbitrary) way of accounting for these differences is to simply average the survey values and the revised calculated values to result in Case C of Fig. 1. This process picks up some of the "relative" aspects of the survey weightings and some of the "absolute" aspects of the calculated weightings.

Formation of Benefit/Cost Ratings

The purpose of deriving the cost weightings is, of course, to make it possible to combine individual benefit/cost ratios into an overall benefit/cost rating. The weightings can be applied in either an arithmetic or a geometric averaging process:

$$R_i = \frac{\sum_j \omega_j f_{ij}}{\sum_j \omega_j} \qquad \text{arithmetic}$$

$$R_i = \left[\prod_j f_{ij}^{\ \omega_j}\right]^{\frac{1}{\sum_j \omega_j}} \qquad \text{geometric}$$

In practice, it has been found that the geometric process is preferred since it leads to a more reasonable mean value when widely differing individual values are encountered. As in the case of individual benefit/cost ratios, a value of the benefit/cost rating greater than 1.0 indicates superiority of the option being examined, relative to the baseline option.